TAMPEREEN TEKNILLINEN YLIOPISTO
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MICRO HYDRO AND PHOTOVOLTAIC AS ALTERNATIVES FOR ELECTRIFICATION OF REMOTE VILLAGES IN NEPAL

Master of Science thesis

Examiner: Professor Risto Raiko
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ABSTRACT

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Nepal is a least developed country in the Himalayas, which has 83,000 MW of economically exploitable hydro recourses, but is currently facing electricity crisis with around 1,000 MW of estimated consumption and 700 MW of production capacity. Majority of the population resides in rural areas where the electricity coverage is only 30%. The Finnish and Nepalese governments initiated Rural Villages Water Resources Management Project (RVWRMP) in 2006 to continuously improve the quality of life, enhance environmental conditions and increase rural livelihoods opportunities.

In this thesis the economic and environmental performance of micro hydro, single household photovoltaic system (SHS) and photovoltaic micro grid was estimated. This was done by calculating levelized cost of electricity (LCOE) for each technology in different scenarios. The scenarios were created to correspond to actual villages in rural Nepal with different number of households and length of power distribution network. The photovoltaic systems were calculated to provide the same level of electricity services as micro hydro with corresponding photovoltaic array and battery sizes. The main difference between these technologies is the load factor which is typically low for micro hydro schemes. The data is mostly from information of RVWRMP and literature. In addition, a short user survey was conducted during a field visit to Nepal to obtain information regarding user experiences of micro hydro electricity.

The results show that each technology has its strengths and weaknesses. The main advantage of micro hydro is its low LCOE when the load factor is above 60%. However, with lower load factors SHS and micro grid provide excellent alternatives. The lower the load factor the bigger the number of households and the shorter the length of PDN that are required for micro hydro to break even with SHS and micro grid. Each technology also offers electricity produced by minimal adverse environmental effects and outperforms traditional off-grid solutions like diesel generators. The main results of the questionnaire show that most common electrical appliances were lights and mobile phones and that majority of the electricity users were positively affected by the availability of electricity. The energy crisis of Nepal is similar to that of many other least developed countries with one important exception; Nepal has vast hydro recourses, which will have significant effect on the rural population and the whole country. This thesis reviewed three technologies to offer electricity for the rural population, all of which have their preferred working environment, which are described more closely in chapter four.

TIIVISTELMÄ

TAMPEREEN TEKNILLINEN YLIOPISTO
Ympäristö- ja energiatekniikan koulutusohjelma
JÄRVENPÄÄ, JUKKA: Mikrovesivoiman ja aurinkosähkön vertailu maaseudun kylien sähköistämisessä Nepalissa
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Nepal on köyhä kehitysmaa Himalajalla. Sillä on 83000 MW taloudellisesti kannattavia vesivoimaresursseja, mutta siitä huolimatta se kärsii sähkön tuotannon puutteista arvioidun kulutuksen ollessa 1000 MW ja tuotannon 700 MW. Suurin osa maan väestöstä asuu maaseudulla, jossa sähköisyysaste on vain 30 %. Vuonna 2006 Suomen ja Nepalin valtiot perustivat Rural Village Water Resources Management Project -nimisen hankkeen (RVWRMP), jonka tavoitteena on jatkuvasti parantaa elämänlaatua ja ympäristön tilaa sekä kasvattaa maaseudun toimeentulon mahdollisuuksia.

Diplomityössä tarkasteltiin mikrovesivoiman, talouskohtaisen aurinkosähköjärjestelmän (SHS) sekä mikroaurinkosähköjärjestelmän taloudellista ja ympäristöllistä toimintakykyä. Se toteutettiin laskemalla tuotetun sähkön kilowattihinta erilaisissa skenaarioissa, jotka luotiin vastaamaan todellisien kylien ominaisuuksia eri lukumäärillä talouksia ja eripituisilla sähkönsiirtoverkoilla. Aurinkosähköjärjestelmät mitoitettiin tuottamaan samat sähkön ominaisuudet kuin mikrovesivoimalla. Kuormituksen käyttösuhde oli merkittävin tekniikoita erottava tekijä, mikä on tyypillisesti alhainen mikrovesivoimalla. Materiaalina käytettiin pääasiassa RVWRMP-projektin tietoja. Lisäksi maastovierailulla toteutettiin lyhyt mikrovesivoiman käyttäjäkokemuksia mittaava kysely.

Tuloksista havaittiin, että mikrovesivoiman merkittävin etu on sen alhainen kilowattihinta, kun kuormituksen käyttösuhde on yli 60 %. Alhaisemmilla käyttösuhteilla SHS ja mikroaurinkosähköjärjestelmät tarjoavat erinomaisen vaihtoehdon vesivoimalle. Mitä alhaisempi kuormituksen käyttösuhde on, sitä enemmän vaaditaan taloja ja sitä lyhyempi sähköverkon tulee olla, jotta mikro vesivoiman kilowattihinta alittaisi kilpailevien teknologioiden hinnat. Tämän lisäksi kaikkien teknologioiden negatiiviset ympäristövaikutukset ovat minimaaliset, jonka vuoksi ne ovat parempia vaihtoehtoja valtion verkon ulkopuoliseen sähköntuotantoon kuin perinteiset dieselgeneraattorit. Kyselytutkimuksen päätuloksista nähtiin, että yleisimmät sähköä käyttävät laitteet talouksissa ovat lamput ja matkapuhelimet ja että sähkö oli vaikuttanut positiivisesti pääosaan käyttäjistä. Nepalin energiakriisi on yhdenmukainen muiden kehitysmaiden kanssa yhtä tärkeää poikkeusta lukuun ottamatta; maalla on erittäin laajat vesivoimaresurssit, joilla tulee olemaan merkittävä vaikutus maaseudun väestöön ja koko maahan. Tämä diplomityö arvioi kolmea teknologiaa maaseudun sähköistämiseen, joilla kaikilla on oma suositeltava työympäristönsä. Nämä ovat tarkemmin esiteltynä kappaleessa neljä.

PREFACE

This Master of Science Thesis has been done at the Department of Chemistry and Bioengineering in Tampere University of Technology. The supervisor of the thesis was Kari Leppänen and the examiner of the thesis was Professor Risto Raiko.

Firstly, I would like to thank Kari Leppänen for providing me with this interesting topic, hosting me during the visit in Nepal and for the guidance and feedback during the work. I would also like to express my gratitude to hydropower specialist Roshan Shah who shared his knowledge of micro hydro with me and supported me during the field visit in rural Nepal. In addition, I would like to thank Professor Raiko for his guidance and thoughts during the thesis. I would also like to thank Riikka Nieminen for the important feedback and support she provided. Finally, I would like to thank my wife and family for the absolute support they have provided me throughout my studies.

Tampere 21.12.2014

Jukka Järvenpää

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LIST OF SYMBOLS AND ABBREVIATIONS

PV	Photovoltaic
RVWRMP	Rural Villages Water Resources Management Project
LCOE	Levelized cost of electricity (Discounted annual building and operation costs divided by annual electricity generation)
GDP	Gross domestic product
AEPC	Alternative Energy Promotion Center
GESI	Gender Equality and Social Inclusion
VDC	Village Development Committee, a rural municipality
MHP	Micro hydropower project
MHS	Micro hydropower system
ESAP	Energy Sector Assistance Program
RERL	Renewable Energy for Rural Livelihood
RMB	Renminbi, Chinese currency
EUR	Euro, European currency
USD	United States Dollar
NPR	Nepalese Rupee
SHS	Solar home system
HH	Household
PDN	Power distribution network
BoS	Balance of System
PCU	Power-conditioning unit
CRF	Capital recovery factor
MGRID	Micro grid

1 INTRODUCTION

Micro hydro power plants and photovoltaic (PV) systems offer a renewable, carbon free electricity source. At the current state of development, both of these energy sources are good alternatives over grid extensions in remote areas with rough terrain. Hydropower has been around since the 19th century and the technological developments have focused on raising the efficiency of the turbines and electronic equipment. Photovoltaic cells were developed in the mid-20th century with a major industry growth in the last decade. (Boyle, 2004) Both of these energy sources are well suited for off-grid electrification.

In 2006 the Finnish and Nepal governments initiated the Rural Village Water Resources Management Project (RVWRMP). Currently, in 2014, the project is in its II Phase, set to complete by August 2015. The main goal of the project is to continuously improve the quality of life, enhance environmental conditions and increase rural livelihoods opportunities. RVWRMP covers multiple sectors, one of which is renewable energy. (Rural Village Water Resources Management Project, Phase II, 2014) Major effort of this sector is micro hydro development. There are 17 micro hydro plants developed, seven of which have already been built. The focus of this master's thesis is renewable energy, and it is conducted in cooperation with the Technical University of Tampere and the RVWRMP.

The emphasis of this thesis is economical comparison between already built micro hydro power plants, and PV systems designed for independent electricity production. The main question is whether solar PV systems are more economical alternatives for rural electrification than micro hydro. It has been shown that solar PV systems offer a good alternative over grid extensions and fossil fuel burning generators. In these projects the levelized cost of energy (LCOE) of solar PV systems has been around 0.25 USD/kWh (~0.20 EUR/kWh) and diesel generators at around 1.3 USD/kWh (~104 EUR/kWh). (Akikur, et al., 2013) The levelized cost of electricity indicates the annual expenditure per produced kWh of operating and building the power plant.

The economical comparison between these two energy sources is important to address because it can be used to develop sustainable energy systems in the rural villages in question. The direct impact of electricity is believed to enhance the quality of life through night time illumination, creation of job opportunities, women empowerment, and improved social interaction. In addition to the economical comparison, a brief environmental comparison is done to obtain a deeper understanding on the effects of the use of renewable energy technologies in rural off-grid electrification. This is important because the environmental effects also influence the favorability of each technology.

2 THEORETICAL BACKGROUND

The theoretical review of this thesis is divided into four sub categories: introduction of Nepal, rural electrification, hydropower, and photovoltaic. This chapter is used to present all the necessary information required to understand the calculations performed later on in the thesis, the current electricity situation in Nepal and the advantages and weaknesses of photovoltaics and micro hydro.

The purpose of this study is to find out the breakeven point (in terms of households served) under which PV is more economical than micro hydro for rural electrification in Nepal. The work is primarily based on literature review and a short visit to Nepal with all the required knowledge gathered from the micro hydro projects' data of RVWRMP. The conclusions of this thesis will be used for the decision making of Phase III of RVWRMP.

2.1 Introduction of Nepal

Nepal, with a population of 26.5 million, is situated between China and India in the Himalayas. It stretches some 900 km wide from east to west and 200 km from north to south. The lowest plains of Nepal are only 70 meters above sea level, and the highest peaks raise towards 9,000 meters (Mt. Everest 8,848 m). The country is divided into three categories by the terrain: coming down from north is the northern range called the mountains, the mid-range is called the hills and the southern range is called the terai (flat land). In addition to terrain categorization, Nepal is also divided into five administrative development regions. These are the Eastern, Central, Western, Mid-Western and Far-Western Development Region. RVWRMP works in the Far and Mid-Western Development Regions with its headquarter located in Dhangadhi, Kailali district, in the Seti zone. (Government of Nepal, National Planning Commision Secretariat, 2013)

Currently Nepal is rated as a least developed country, but it is working hard to upgrade its status to a developing country by focusing on green technology and climate change issues in development programs (Gurung, 2013). The annual gross domestic product at current prices is estimated at 717 USD (576 EUR) for 2013/2014 with an economic growth of GDP at 3.6%. Over 80% of the population resides in rural areas where agriculture is the main source of income. The industrial sector in Nepal is very small with 7.7% of the GDP, comprising mostly of the processing of agricultural products. (Government of Nepal, National Planning Commision Secretariat, 2013) (Gautam, et al., 2009) The rural infrastructure is underdeveloped, which also affects energy usage. Since there is no electricity or roads, the villagers are forced to use traditional energy sources for heating and cooking. Animal dung, fuel wood and agriculture residue are popular energy sources, accounting for 87% of the total energy consumption in Nepal (Parajuli, et al., 2013). This leads to a few key difficulties affecting the rural population. The continuous gathering of wood is very time consuming and also accelerates deforestation. Deforestation is a major problem in the hills and mountains because it enables landslides which are common during the rainy season. In addition, the inefficient open fireplaces and wood burning stoves are a cause of respiratory diseases because chimneys are not being used in rural Nepal. (Gautam, 2014) Renewable energy technologies are a key in changing Nepal to a developing country.

2.1.1 Energy sector in Nepal

World Bank estimates that approximately 63% of the population still lack access to electricity (Banerjee, et al., 2011). The three-year plan of 2013 to 2016 is targeting renewable energy technologies in the form of biomass, solar, micro and small hydro energy programs to increase the electricity coverage in Nepal. The government is planning to install 400,000 solar electricity systems in off-grid areas, 8 solar mini-grids, 12 battery collection centers, 1,300 institutional solar electricity systems and also 100,000 city-solar electricity systems in places where there is still no national electric grid connection. There is also a plan to generate 15 MW of electricity from micro and small hydro, establish 5 local grids, install and improve 2,950 water mills and conduct 9 feasibility studies on connecting small and micro hydro to national grid. The goal of biomass technology is to achieve smokeless homes with clean energy technologies. This is done by installing 80,000 household biogas plants, 900 communal plants, 50 commercial plants and 10 plants that use municipal waste to produce energy. The total electricity generated through these systems is calculated to provide electricity for additional 8% of the rural population in Nepal. (Gurung, 2013)

Another important aspect in the three-year plan is the income generating activities which arise from the above-mentioned goals. New employment opportunities will be developed to 19,000 employees with 1,300 new enterprises and the improvement of 2,800 existing enterprises. Renewable energy technologies are also used for improving agricultural productivity with irrigation waste management. In addition to local trade and services, the government goal is to eventually integrate climate change into renewable energy planning and achieve sustained revenue from carbon trade. (Gurung, 2013)

In the year 2000 Nepal introduced a new policy which addresses renewable energy technologies. It is designed to bridge the financial gap between the cost of energy and its affordability by the poor. The financing scheme of rural electrification projects consists of community equity or private investment, subsidy from government, and credit from financing institutions. The subsidies have been recalculated in 2006 and 2008 to keep in line with the high inflation rate in Nepal. There are some discrepancies in the subsidy system like the requirement for 10% productive end uses and the maximum demand limited to 120 W per household. The productive end use requirement for electricity can be hard to meet with only 120 W of power. There are many improvements to be made in the subsidy system, but it can already be seen that subsidies are affecting rural electrification.

Promoting these policies has led to the growth of the micro hydro and solar system markets in Nepal. However, a negative effect can also be seen in the financial markets where a change towards equity and subsidy based system is reducing the impact of credit from financing institutions. The latter kind of development is not in favor of the poor because they have very little, if any, equity for electrification projects. (Mainali & Silveira, 2010)

2.1.2 Electricity

Electricity demand in Nepal has been growing at a rate of approximately 10% per annum (Nepal Electricity Authority, 2013). Currently the peak demand is 1,026 MW (2011/2012) with a generation capacity of only 720 MW (Ministry of Finance, 2013). It is clear that Nepal will suffer from a massive electricity shortfall in the coming years. The Nepalese authorities are giving an optimistic estimate that this shortfall will last for 3-4 years. (Nepal Electricity Authority, 2013)

The country has been under several reforms which have slightly increased electricity supply, but this increment has not been sufficient to cope with the quick rise in demand. The demand has risen from 885 MW in 2009/2010 to 1,026 MW in 2011/2012. This trend will continue in the coming years as the earliest data from 2012/2013 show that in the first eight months the demand has gone up to 1,094 MW. (Ministry of Finance, 2013) There is large disparity in electricity distribution in the country with 90% electricity access among the urban population as compared to only 30% among the rural population. Altogether, only about 40% of the total population has access to electricity. (Banerjee, et al., 2011)

The major problems in electricity markets and policies are the price of electricity, underinvestment in electricity generation, technical and non-technical losses, and rural electrification. The electricity prices in Nepal are so low that they do not cover the costs of production, which has led to significant economic losses for the Nepalese electricity authorities. The low prices of electricity also affect the interest to invest in power generation because there are no working tariffs to support the system costs and capacity expansion. Technical losses are also derived from too low electricity prices because there are insufficient funds for maintenance of the grids. Non-technical losses are similarly affecting the grid stability when electricity thieves are putting extra load on already sensitive grid. Rural electricity is of key importance to Nepal because majority of the population resides in rural areas. The electrification of rural villages has some difficulties that stem from the lack of basic infrastructure. This affects the cost of extending the grid when the terrain is very rough and has high altitude variations. The basic lack of funds for electricity generation and grid development is believed to stem from lack of interest by political parties. This is reflected in policies which support the use of imported fossil fuels. (Nepal & Jamasb, 2012)

Micro hydro and other renewable energy technologies have had a positive impact on rural electrification in locations far away from the national grid. These systems often work by creating an island where electricity is available to the villagers and those who live close by. Multiple islands not too far from each other can be interconnected to strengthen the grid accountability. These island grids are also called micro grids, and they face some challenges of implementation in Nepal. It is important to keep the voltage and frequency control at desired levels at all times to enhance the stability of the grid. When connecting multiple power generators (Micro hydro, PV) to the same grid they all need to be protected individually with solid state circuit breakers. Another important factor is the load sharing in which the load needs to be divided to all of the power generators connected to the grid. This means that when there is excess power, some generators can be shut down to save operating hours. (Shailendra & Stoa, 2014)

The national electricity grid runs mostly in the terai region where it stretches from east to west. The grid is either 132 kV or 66 kV with 220 kV line under construction in many parts of the country. The largest cities and surrounding areas are all part of the national grid, but the grid is still missing for majority of the population. As the current electricity consumption exceeds the production, the national grid is in a very unsteady state. The government is trying to reduce the number of random blackouts by load shedding in the biggest cities, but there can still be many unscheduled blackouts daily. The difference between production and consumption is the biggest problem in the electricity sector, but the grid itself is also unstable because of poor design and maintenance. (Nepal Electricity Authority, 2013) An example of the low voltage grid inside the capital of Kathmandu can be seen in figure 2.1 below. To overcome the continuous problems with blackouts in the already built national grid, both the electricity production and the condition of the grid need to be fixed.

Figure 2.1. *Electricity grid in Kathmandu.*

2.2 Rural electrification

Areas with low energy demand and scattered population are often uneconomical for grid extensions because of the high capital cost of civil works. Grid extensions also suffer from inefficiency and unmanageable distribution network because extensions are done by connecting single villages together, which leads to disorganized grid patterns. In this study, the previously built micro hydro power plants are compared with PV systems to find out if they suit better for rural electrification in some cases. (Kamalapur & Udaykumar, 2011)

Successful rural electrification programs have been implemented in many developing countries. Most of these countries do not have as rugged terrain as Nepal, but some important lessons can still be learnt from these programs. Institutionally it is important that the implementing agencies have operating autonomy so that their main objective and responsibility is rural electrification. Nepal is a country with a history of political instability, and this still shows in high corruption rates and lack of public trust in the government (International Institute for Democracy and Electoral Assistance, 2013). When politicians are able to interfere with the funds it creates a severe problem with public funding, and is very harmful for the success of the program (Barnes & Foley, 2004).

Cost recovery is another important factor in a successful rural electrification project. It is of crucial importance of all organizations working with rural electrification projects to pursue cost recovery to maintain a healthy economic environment for the project. Charging enough for the consumed electricity will help on recovering all the costs, but somehow there is a belief that the price needs to be low in rural areas. This often leads to market prices that are below production costs, which is an unsustainable way to promote rural electrification. It is clear that rural households cannot pay the installation costs of the system on short payback periods, but it has been shown that they are willing to invest in systems with reasonable payback periods. (International Institute for Democracy and Electoral Assistance, 2013) A big problem in Nepal is the unsustainable pricing of electricity for rural households. In many cases, the electricity price for the customer is less than that for the producer. This is one important factor which the decision makers need to address. (Banerjee, et al., 2011)

2.2.1 Effect of electricity on wealth

Electricity in rural areas is one important factor in improving the quality of life of the residents, but in order for this to happen all other necessary conditions must be met. The most important of these conditions are health and education services, water supply, secure land and availability of agricultural inputs. (Barnes & Foley, 2004) The positive effects of electricity on rural households in Nepal were evaluated in a World Bank survey study in 2009.

The study focused on evaluating the effect of electricity on consumer surplus, health, education, fertility, women empowerment, and greenhouse gas emissions. Consumer surplus means the savings per household when they switch to electricity. In rural households, this comes mostly from lighting when kerosene lights are changed to electric lights. It was shown that households with electricity saved about 50 NPR (~0.40 EUR) a month on kerosene and therefore theoretically could spend that on something else. Upon further investigation, it was show that the good electric lighting allows the residents to continue their income generating activities, household activities, and small productive activities, like sewing, in the evening. This leads to increasing off-farm income and expenditure per capita. It was also shown that the education level was higher in households with electricity and the time spent studying in the evening was higher in these households. Health effects of electricity were mainly positive, with households with electricity having fewer respiratory or gastrointestinal problems than those without electricity. However, availability of electricity increased respiratory problems of adult males, which was believed to emerge from spending more time indoors watching TV. There were no major effects for women’s fertility and empowerment apart from a general small rise (<1% each) in the time spent for leisure and income generating activities. Currently it is estimated that about 1 million kg of CO_2 is saved, as kerosene savings, by using hydropower in rural electrification. This is a major positive impact of electricity, as the study showed that households release 3.6 kg less CO_2 emissions per month when they have electricity. (Banerjee, et al., 2011)

It is clear that the current rural hydro schemes are unsustainable due to the negative income for service providers, but it is important to note the other benefits listed above in the overall evaluation of rural electrification programmes. The conclusions of the study show that, after taking into account the consumer surplus, the households save more money than they use for electricity. (Banerjee, et al., 2011) This means that there is room for price increase.

2.2.2 Environmental aspects of PV systems and micro hydro

Solar photovoltaic technology is often rated as the most environmentally friendly energy production technology because it produces no greenhouse gas emissions or sound pollution, its capacity can be increased easily if needed, and it requires minimal maintenance. Hydropower is currently the most important renewable energy source in the world, but its reputation is not very good due to the many negative experiences that have emerged with large-scale hydro plants and their construction. (Boyle, 2004)

The most infamous accident was the failure of the Banquao Reservoir Dam in China in 1975, which took the lives of 170,000 people. In addition to the dangers of constructing massive dams, they also affect the river and grassland ecosystems, which can have irreversible effects on the species of the area. The large reservoirs also emit methane gas, which is harmful for the environment. However, the micro hydro is considered a much better option for electricity generation as it does not require dams for storing water, therefore having minimal effect on the ecosystem of the river. (Akikur, et al., 2013)

The manufacturing of photovoltaic cells is harmless for the environment unless, for example, a major accident at the manufacturing plant occurs. Silicon itself, the main ingredient of solar cells, is harmless. However, small amounts of toxic chemicals are used in the manufacturing of some cell types. Thus it is important to pay attention to the plant design in order to avoid the release of these chemicals. (Boyle, 2004)

2.2.3 Future plans

The Alternative Energy Promotion Centre (AEPC), established in 1996, is the main promoter of renewable energy in Nepal. Its mission is to make renewable energy a mainstream resource through increased access, knowledge and adaptability contributing for the improved living conditions of people in Nepal. The objectives of AEPC are to popularise and promote the use of renewable energy technology, to raise the living standard of the rural population, to protect the environment, and to develop commercially viable alternative energy industries in the country. AEPC is approaching these objectives through Public Private Partnership model with a demand-based method in which the public sector of AEPC works for capacity building, technical and financial assistance, coordination, and quality assurance. Therefore, the focus is on preparing the rural population for electricity services and providing information and guidance through the whole process. Simultaneously, in the supply side, the private sector works for manufacturing, supply and installation, and after sales services.

AEPC is targeting to add 25 MW to its mini/micro hydro production in the period from 2012 to 2017. In addition, the plan is to install 600,000 single household systems in the same time. These come from a number of rural energy projects that are funded by the government and donors. Currently AEPC is not supporting solar micro grids, but they have been designing two pilot systems to promote the use of solar mini grids. The designs were completed in fiscal year 2012-2013. AEPC is also promoting gender equality through its Gender Equality and Social Inclusion (GESI) unit. (Alternative Energy Promotion Centre, 2013) The national target of Nepal is to achieve 100% electricity coverage by the year 2027 (Nepal Electricity Authority, 2013).

2.3 Hydropower

Hydropower exploits the energy of water in rivers by guiding the flow through a turbine that is connected to a generator. The earliest waterwheels were built around 200 BC in the Middle East. In 800 AC England, water mills (both vertical and horizontal) became common and by 1,100 AC there were already about 5,000 mills, one in almost every settlement. (Boyle, 2004)

There were three main types of waterwheels at the end of the 18th century: overshot wheel, undershot wheel and breastshot wheel. The overshot wheel is driven by falling water from above whereas the pressure of water from beneath the blades drives the undershot wheel. In breastshot wheel, water comes from a channel to the middle of the wheel. Mills were used for various purposes in addition to traditional uses, e.g. mining, ironwork, papermaking, and wool and cotton industries. Water was the main source of mechanical power before the industrial age (Boyle, 2004) and the technology had advanced to a point where the efficiency had reached as high as 70% (Paish, 2002). Modern day turbines were developed in the 19th century when rapid developments were being made in the field of electrical engineering (Boyle, 2004, p. 160). Two major changes in waterwheels were the use of guide vanes and submerging the turbine in water. Guide vanes are used in turbines to change the direction of the flow to maximize the conversion of kinetic energy to mechanical energy (Raiko, 2013). Submerging the turbine allowed greater rotation speeds that are better suited for high RPM electrical machines (Boyle, 2004, p. 161).

In the late 19th and early 20th century, hydropower became the fastest growing electrical energy source in the world. Power plant capacities rose from mere kilowatts to megawatts in less than a decade. (Boyle, 2004)

2.3.1 Current status

Hydropower is the largest renewable energy source worldwide. In 2011 it contributed about 16% (22,126 TWh) of the world’s electricity generation (International Energy Agency, 2013). The installed capacity has been slowly growing from the early 20th century. The growth in hydropower is mostly from the improvements of already built plants with more efficient equipment and building of large-scale plants (Boyle, 2004). The annual growth rate has been around 50 TWh for a few decades, a good growth rate for a renewable energy source. However, the total electricity production has been rising faster than hydropower as illustrated in figure 2.1. (International Energy Agency, 2013).

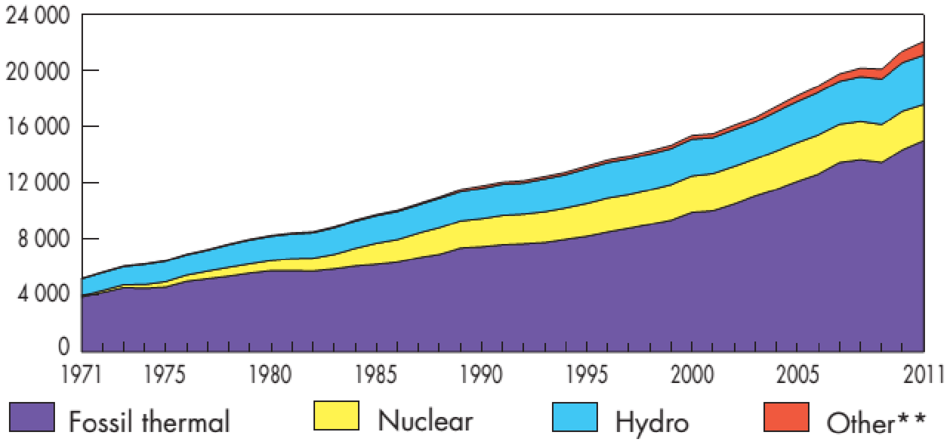

Figure 2.1 *World electricity generation from 1971 to 2011 by fuel (TWh) Other includes geothermal, solar, wind, bio-fuels, waste and heat* ***(****International Energy Agency****,*** *2013****)****.*

In 2008, China had 18% of the total electricity generated through hydropower and was experiencing the highest growth rates worldwide (International Energy Agency, 2010). From 2010 to 2020, China plans to add 220 GW to the already produced 213 GW, which will boost its growth rate even more and make it the largest hydropower user by an even larger margin (Worldwatch Institute, 2010) (Ecology, 2013). Developed countries can hardly compete with China's growth rates because there are still plenty of untouched sites for hydropower unlike in Europe, for example (Paish, 2002).

Hydropower plants are divided into two categories: small-scale hydro and large-scale hydro. Small-scale hydro is estimated to generate approximately 5-10% of the total hydropower capacity. The upper limit of small-scale hydro is usually at 10 MW, however there are many different classifications around the world. In China, for instance, the upper limit is 25 MW. (Boyle, 2004) The European Small Hydropower Association has evaluated that Europe has over 13.5 GW of installed small-scale hydropower. This number is estimated to increase up to 17.3 GW by the year 2020. (The European Small Hydropower Association, 2010) As most of the cost efficient large-scale sites have already been built, this rise is attributed to small-scale hydro capacity (Paish, 2002). In addition, environmental reasons are limiting the large-scale hydro projects in developed countries (Boyle, 2004, p. 173) whereas in the developing countries small-scale hydro is found to be a good alternative for low cost, off-grid installations (Paish, 2002).

This thesis focuses on small-scale hydro, which is further divided into three sub categories: micro, mini, and small. Micro plants are under 100 kW, mini plants in the range of 100-500 kW, and small plants between 0.5-10 MW. (Boyle, 2004) All plants built in Nepal fall into the micro category, with highest power output of 100 kW.

2.3.2 Micro hydro scheme

Micro-sized plants are well suited for rural electrification projects. They are often off-grid installations that produce electricity for a small community. This community benefits from electricity in a few key ways, first of which is the illumination during night time that helps students to do their homework in the evenings. Second, the electricity also supports livelihood projects. Third, the building of micro sites creates employment opportunities for the local people. All these benefits help the villagers to break out of poverty. In addition to communal benefits, the high cost of extending grids is another a point to consider when planning these sites. These are the key aspects that form a solid base for assessment of advantages of micro hydro. (Department of Energy, DOE, 2009)

A typical micro hydro plant consists of diversion weir and intake, settling basin, headrace and headtank, penstock, and powerhouse (Figure 2.2).

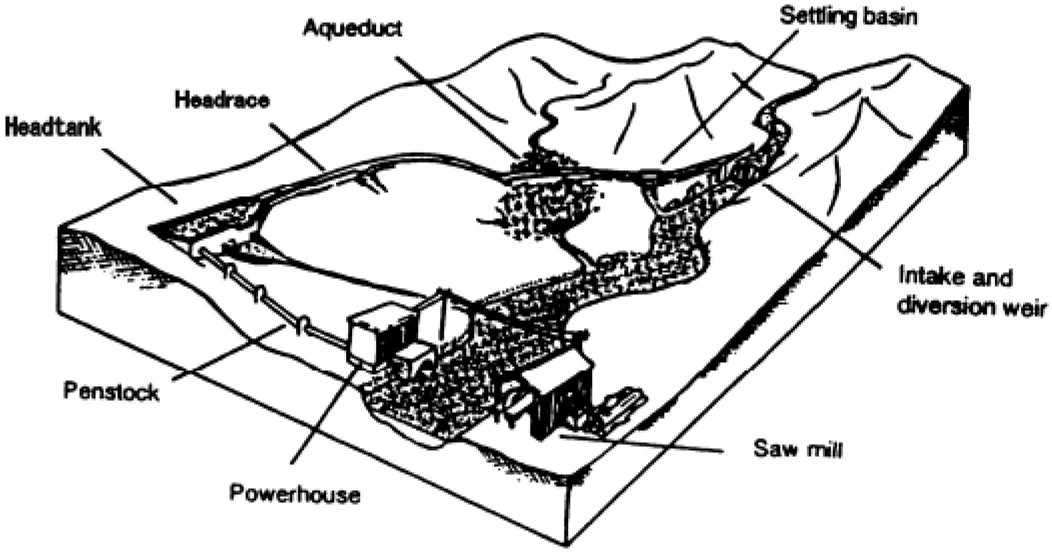

Figure 2.2 *Major components of a micro hydro scheme (Department of Energy, DOE, 2009).*

Diversion weir is a barrier on the side of the river that has an opening into the settling basin. Its function is to divert water from the river to the settling basin. Settling basin is a part of the canal that carries water to the turbine and keeps away all sand and silt from the water before flowing any further. After the settling basin comes the headrace which leads the water into the forebay or turbine. At the end of the headrace comes the headtank that works as a settling basin at the end of the canal, preventing sand or other trash from entering the penstock. The penstock is located beneath the water surface in the headtank and it provides the pressurised water to the turbine. At the end of the penstock are the water turbine and generator which work together to convert the kinetic energy of water to electrical energy. (Department of Energy, DOE, 2009)

Turbines designed for hydro plant applications convert water pressure into mechanical energy and later into electrical energy in the generator. The crucial parameters in hydropower are the head and the flow of water. Head is the drop of height from the headtank to the turbine as described in figure 3 below. Heads are classified by their height to high, medium or low head. High heads are over 100 m and low heads under 10 m, with medium heads between 10 m and 100 m.

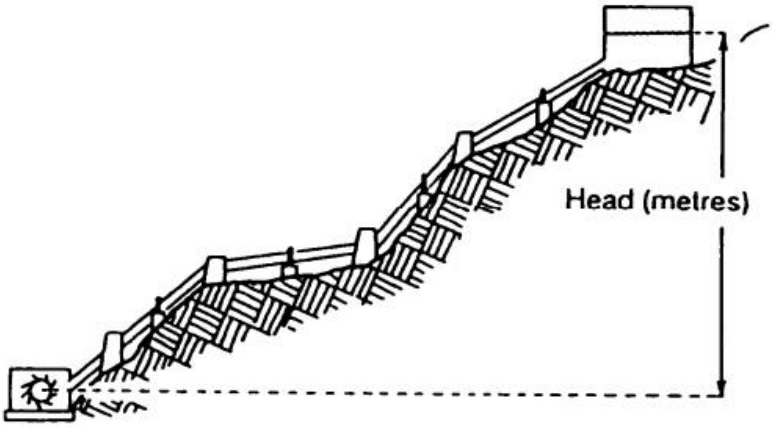

Figure 2.3 *Head is the vertical height through which water drops (Department of Energy, DOE, 2009).*

The higher the head the more pressurised the water. At the depth of 50 meters, the pressure of water is approximately 6 atm (6.08 bar). (Boyle, 2004)

2.3.3 Physical background

In physics, power is the amount of work done in a period of time [J/s] and its unit is watt. The power of the system is proportional to the product of the volume flow rate and pressure head as described below (1)

$$P = \eta * \rho * g * Q * H, \tag{1}$$

where P is the power, η is the hydraulic efficiency of the turbine, ρ is the density of water, g is the acceleration due to gravity, Q is the volume flow rate, and H is the effective pressure head. (Paish, 2002) The volume flow can be derived from energy balance when we assume that all potential energy converts to kinetic energy at the bottom of the penstock. Potential energy is converted to kinetic energy as described below (2)

$$\frac{1}{2} * M * v^2 = M * g * H, \tag{2}$$

which then reduces to (3)

$$v = \sqrt{2 * g * H} \text{ [m/s]}. \tag{3}$$

We then assume that water flows in a circular area of A square meters, from which we can derive the volume flow Q which is cross-sectional area times the speed of water flow. Therefore, the volume flow becomes (4)

$$Q = A * \sqrt{2 * g * H} \text{ [m}^3\text{/s]. (Boyle, 2004)} \tag{4}$$

There are many losses in the system that reduce the efficiency, starting from the canal and ending at the transformer near the power output. The length of the canal and the head affect canal efficiency. This is described below (5)

$$E_{canal} = 1 - (L_{canal} * e)/H, \tag{5}$$

where *e* ranges from 0.002 to 0.005 depending on the built quality and materials of channel. Penstock efficiency is between 0.9 and 0.95 depending on the length of the penstock.

Typical large-scale turbines reach efficiencies of 0.9 while small-scale turbines are between 0.6 to 0.8. Efficiency of the generator is in the range of 0.8 to 0.95 depending on the capacity of the generator. Drive system losses are about 0.97 and line losses between 0.9 and 0.98 depending on the length of transmission. Finally the transformer has efficiency of 0.98. With all these losses combined, the total efficiency is approximately 0.4 to 0.7 depending on the quality of the different components. (Department of Energy, DOE, 2009)

2.3.4 Turbines

Turbines convert the energy of flowing water into rotational energy of the shaft. Generally, turbines are classified into impulse or reaction turbines. Reaction turbines are submerged in water where the pressure rotates the runner blades. Impulse turbines on the other hand work by an impulse jet that rotates the runner blades as illustrated in figure 2.4.

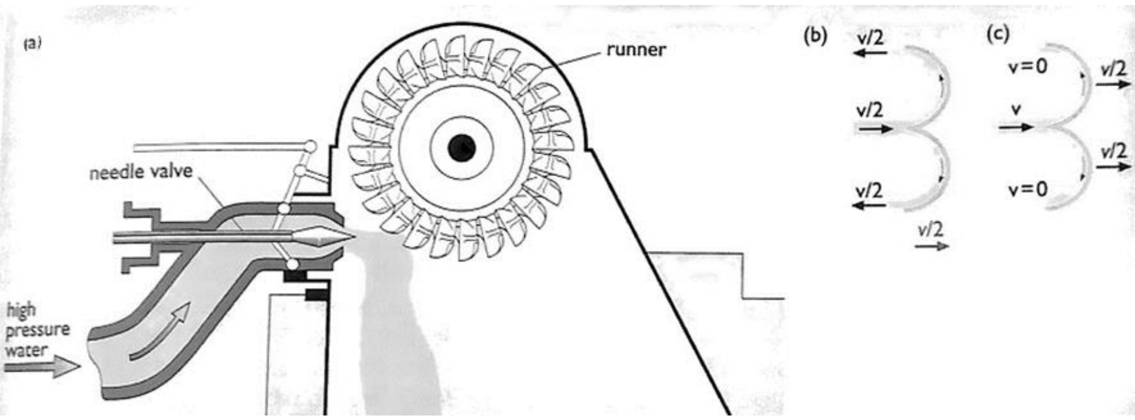

Figure 2.4. *Pelton wheel turbine: (a) vertical section; (b) water flow as seen from moving cups; (c) actual motion of water and cup (Boyle, 2004).*

The water enters the runner cups at the speed of *v* and leaves the cups at the speed of *v=0*. Therefore, all the kinetic energy of water has been transformed into rotational energy of the runner by changing its direction in the runner cups. The most common turbine in hydro applications is a reaction turbine called the Francis turbine, however, impulse turbines are often better alternatives in SSH due to economic considerations. (Department of Energy, DOE, 2009)

The selection of the turbine depends on the site. The most important characteristics are the head and the flow available. In addition to these key parameters, it is also important to consider the running speed of the generator and whether the turbine is expected to run in various flow conditions. All of these characteristics affect the efficiency of the turbine and each turbine has an efficiency maximum at a certain head, flow and rotation speed. Generally, the head can be used to select the turbines used in a scenario as described in table 2.1 below.

Table 2.1. *Impulse and reaction turbines (Paish, 2002).*

Turbine type	Head classification		
	High (>50 m)	**Medium (10-50 m)**	**Low (<10 m)**
Impulse	Pelton	Crossflow	Crossflow
	Turgo	Turgo	
	Multi-jet Pelton	Multi-jet Pelton	
Reaction		Francis (spiral case)	Francis (open-flume)
			Propeller
			Kaplan

The selected turbine should have a shaft speed as close as possible to 1,500 rpm as generators normally work at that speed (Paish, 2002). The most important turbine to consider for small-scale hydro installations is the crossflow turbine because it can be manufactured locally, it is cheap to construct, and easy to install. There is technical data available for the design and it allows a wide range of heads and flows to match the actual site conditions. The applicable limits for cross flow turbine are shown in table 2.2. (Department of Energy, DOE, 2009)

Table 2.2. *Limit of cross flow turbine (at turbine shaft) (Department of Energy, DOE, 2009).*

		Unit	**Lower limit**	**Upper limit**
H_{net}	Net head	m	4	50
Q	Discharge (flow)	l/s	100	820
P	Shaft power output	kW	10	250
b_0	Inlet width	mm	100	1,120
Number of	intermediate discs	-	0	8

2.3.5 Cost estimation

The Department of Energy in the Philippines has made a rough cost estimation for small-scale hydro projects. It includes preparatory works, civil works, electromechanical works, distribution works, and consumer connections. These calculations are shown in table 2.3.

Table 2.3. *Rough calculation of construction cost during planning stage (Department of Energy, DOE, 2009), in Philippines Pesos.*

No.	Description	Formulae	Remarks
(1)	PREPARATORY WORKS	{2+3+4+5}*0.1	Transportation, Clearing, Temporary Works
(2)	CIVIL WORKS	1 to 7	
	1 Intake Facilities	Gabion Dam 1,400 x H x L	H: Height of Dam(m) L: Length of Dam(m)
		Stone masonry dam 5,350 x (HxL)+5,800	H: Height of Dam(m) L: Length of Dam(m)
		Concrete Dam 11,300 x H x L	H: Height of Dam(m) L: Length of Dam(m)
	2 Settling Basin	Long or Mid-Penstock $414{,}500 \times Q^{0.504}$	Q: Turbine Discharge (m^3/sec) (see system layout)
		Short Penstock $372{,}600 \times Q^{0.794}$	Q: Turbine Discharge (m^3/sec) (see system layout)
	3 Headrace	$2{,}950 \times Q^{0.18} \times L$	Q: Turbine Discharge (m^3/sec) L: Length of headrace (m)
	4 Head Tank	$327{,}200 \times Q^{0.5}$	Q: Turbine Discharge (m^3/sec)
	5 Penstock	Civil Works $5{,}300 \times \varphi^{0.571} \times L$	φ: Diameter of Penstock (m) L: Length of Penstock (m)
		Penstock 100 x Unit wt. x L	L: Length of Penstock (m)
	6 Power house Foundation	$33{,}600 \times P^{0.456}$	P: Maximum Output (kW) (include tailrace)
	7 Power house Building	16,900 x P + 139,900	P: Maximum Output (kW)
(3)	ELECTROMECHANICAL WORKS	$520{,}500 \times (P/\sqrt{He})^{0.56}$	Cross Flow Turbine T-13 P: Maximum Output (kW) He: Effective Head(m)
(4)	DISTRIBUTION WORKS	$95 \times X^{0.5541}$	X: No. of HH x Distance^2
(5)	HH CONNECTION	2,900 X + 219,300	X: No. of Household
(6)	OTHERS	{(2)+(3)+(4)+(5)}*0.05	
	TOTAL	(1)+(2)+(3)+(4)+(5)+(6)	

It is important to have an estimate of the actual costs and income of a micro hydro project designed for rural electrification. A study from Indonesia evaluated the costs and benefits of a 17 kW system, built to electrify seven villages with a total population of 650. There were also about 13 public buildings including schools, churches, clinics, district office, district hall, and street lamps. Each house had wall plugs that provided 366 Wh and lamp sockets that provided 429 Wh of energy per day. The total consumption of the houses and public buildings in the district was 335,567 Wh per day with 415,680 Wh power generated, leaving an excess of 80,113 Wh. A system like this has an investment cost of 778,224,202.02 IDR (~51,000 EUR) with annual profits of 44,933,537.85 IDR (~3,000 EUR). The investment payback time is about 17 years and four months, without an interest rate. (Pasalli & Rehiara, 2014)

2.3.6 Hydropower potential in Nepal

There are approximately 6,000 rivers in the country with total length of 45,000 km, and current estimates suggest that these rivers have a discharge of $174*10^9$ m^3. With the steep rising geography, the linear energy density in the rivers is 33 MW/km, thus well suited for electricity production. (Surendra, et al., 2011)

Nepal has the second largest hydro capacity in the world with 83,000 MW of economically and 42,000 MW of environmentally exploitable resources (Banerjee, et al., 2011). Currently the country only produces approximately 650 MW of hydro power, which means that 99% of the total hydropower capacity is still available. The mountain region ranges through the entire country, which means that hydropower can be utilized throughout Nepal. Nepal has given electricity generation licenses for 52 large and small hydroelectricity projects in fiscal years 2010/11 and 2011/12. These projects account for 1,761 MW of new capacity. However, the realization of these projects is still far. (Ministry of Finance, 2013) (Poudyal, et al., 2011)

2.3.7 Review of RVWRMP supported micro hydro power plants

RVWRMP aims at efficient management of the water resources of Village Development Committees (VDCs) (corresponds to Finnish ‘kunta’) with focus on safe drinking water, water for other domestic uses, and sanitation development. In addition, RVWRMP promotes water resources based livelihoods development. Currently RVWRMP supports 17 micro hydro power plants, completed and those under implementation, in six districts. These plants provide electricity for 6,204 households with a total population of 37,152. RVWRMP collaborates with the national Alternative Energy Promotion Centre (AEPC) in the construction of the micro hydro plants in suitable VDCs in the project area by providing part of the required investments, whereas the actual implementation is coordinated by AEPC.

Thirteen of the 17 micro hydro plants are currently in operation, and over 20 kW in power. A short description of these is given in table 2.5. The schemes are listed in order of completion with numbers from one to seven already completed, and the remaining still under implementation. A more in-depth fact sheet of the schemes is given in appendix 1. There are seven micro hydropower projects (MHP) and six micro hydropower systems (MHS). The Energy Sector Assistance Programme (ESAP) has supported the MHP, and the Renewable Energy for Rural Livelihood (RERL) programme has supported the MHS.

The power output of the plants is between 21 and 100 kW with an average of 45 kW. The remoteness of the power plants varies from a one-hour walk from the nearest road head to up to four days of walking.

The remoteness of the micro hydro power plant affects the transportation costs because all electromechanical equipment and building materials have to be manually transported to site location. This means either hiring local people to carry everything or organising voluntary villagers to help in the transportation of the goods. Usually both means are practiced to ensure safe and inexpensive transportation. However, the most remote locations are simply too far for manual transportation. In such situations, the best way to transport the goods is by helicopter. Transportation costs vary greatly between different sites, ranging from mere 1% to 19% of the total project cost, depending on the remoteness of the site and the total weight of the transported goods.

Table 2.4 *Micro hydro schemes of RVWRMP.*

S.N.	Scheme Name	District	VDC	Power Out-put (kW)	Beneficiary households	Beneficiary Population
1	Hoparigad MHS	Darchula	Sipti	50	583	3,881
2	Upper Rilu MHP	Bajhang	Rilu	30	248	1,552
3	Jadarigad MHP	Bajhang	Pouwagadhi	21	245	1,637
4	Kashegad MHP	Bajura	Chhatara	50	677	4,478
5	Kailash Khola V MHS	Achham	Bhatakatiya	25	349	1,967
6	Kailash Khola IV MHS	Achham	Bhatakatiya	35	430	2,727
7	Maubheri Khola MHS	Bajhang	Koiralakot	30	386	2,187
8	Kukurfalna MHP	Humla	Kalika	100	630	3,267
9	Sanni Gad MHS	Bajhang	Kaphalseri	100	1,123	6,663
10	Riting Gad MHS*	Darchula	Sunsera	51	553	3,283
11	Sailigad MHP	Doti	Girichauka	23	240	1,253
12	Lower Rilu MHP	Bajhang	Rilu	22	250	1,509
13	Dogadegad MHP	Bajhang	Masta	46	490	2,748

Load factor is an excellent tool for measuring the performance of a power plant as it indicates how much electricity is used in comparison to the total generation capacity. Load factor is defined as the ratio of the electricity consumption and the total electricity generation capacity. From the 13 plants, nine have the required information to make these calculations. It must be noted, however, that two of the nine plants are still in implementation phase, which means that only lighting loads are available for calculations. The load factors of these nine schemes are illustrated in figure 2.5.

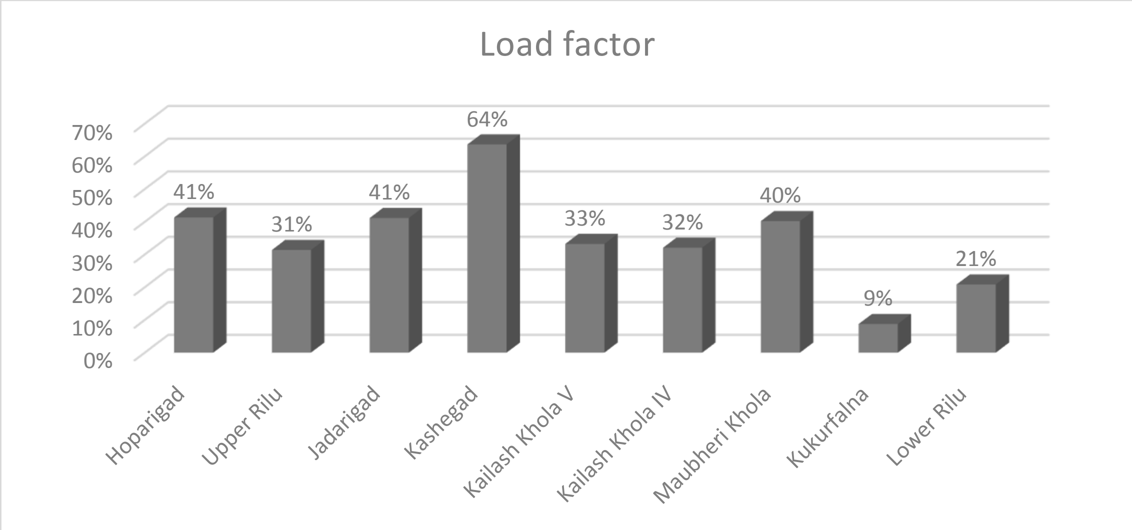

Figure 2.5 *Load factors of RVWRMP supported micro hydros.*

The load factors range between 31 and 64% with an average of 40%, which means that approximately 60% of the total electricity generation capacity is not utilized. Income generating activities play a key role in raising the load factor of each micro hydro since these activities bring valuable income and increase the use of electricity, i.e. it helps to create a positive cash flow towards end users who then increase their electricity consumption.

The main goal of the renewable energy sector of RVWRMP is to create sustainable electricity supply in potential project VDCs, and to encourage the use of electricity for income generating activities. Chhatara is a good example of an active VDC that thrives towards development. More than half of the power generated by the Kashedag MHP in the VDC is used for profitable end uses such as electric mills, telecom tower, computer services and bamboo industry. This allows the VDC to have a steady source of income to invest in development of the area.

2.4 Photovoltaic

Photovoltaic (PV) means electricity generated from light. Edmond Becquerel discovered photovoltaic effect in 1839 when he published his experiments with ‘wet cell’ battery. Charles Edgar Fritts constructed the first solar cell in 1883. This selenium cell was very inefficient (<1%), but the structure of the cell was in many ways similar to the modern day silicon cells.

The breakthrough came decades later in 1950s when scientists studied the effect of light on semiconductors. In 1954 the scientists published a paper on their experiments in which they managed to increase the efficiency of a silicon cell up to 6%. The development of photovoltaic has been active from the 1960 onwards and, when reaching the 21st century, the efficiency of the most advanced silicon solar cells has increased to 24%.

2.4.1 Current status

The progress in PV is expected to continue, and at this rate PV is the fastest growing source of renewable energy (International Energy Agency, 2012). This is well illustrated in figure 2.6.

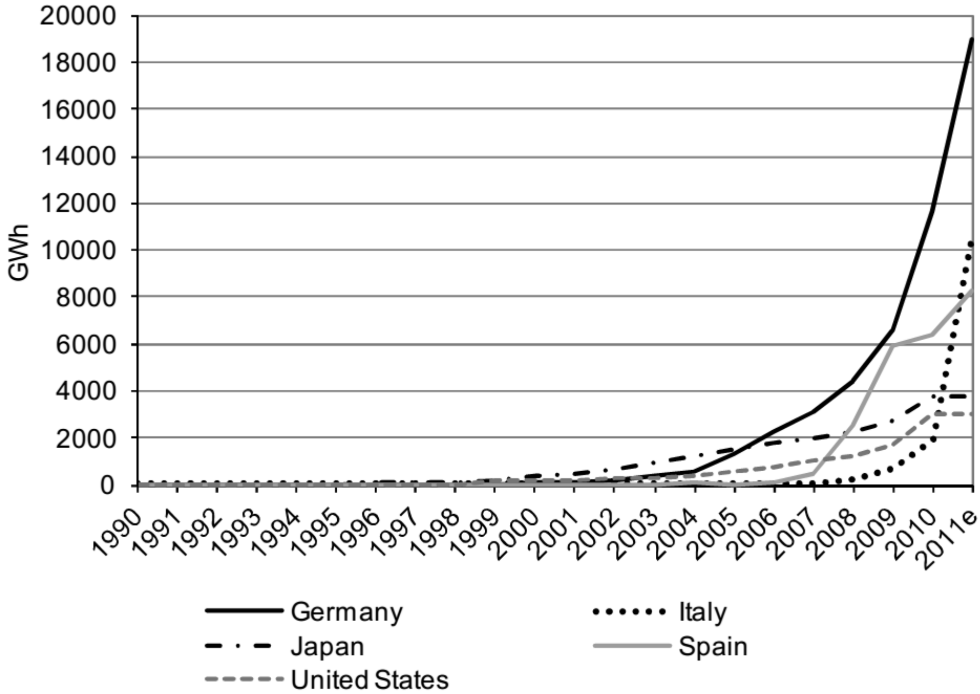

Figure 2.6. *PV electricity in five major producing countries from 1990 to 2011 (International Energy Agency, 2012).*

These countries produced 82.6% of the total PV electricity in the OECD countries in 2011. The illustrated growth rates are something to remember. The past 10 years have been successful years for PV, and the fast growth rate is likely to continue in the future. The renewable energy outlook of the International Energy Agency projects that in the year 2035 the solar PV is expected to be 26 times larger than in 2010. This means an increase from 32 TWh to 846 TWh. The rapid growth rates have already affected the PV generating costs. These costs fell by 44% from 2010 to 2012 alone, and similar progress can be expected in the future. (International Energy Agency, 2012) However, it is important to remember that the total electricity generated by solar PV was only 0.25% of the total electricity generated in 2011 (54 TWh vs. 22,126 TWh) (International Energy Agency, 2012). This means that even with the extraordinarily high growth rates, it will take decades to catch up with traditional energy sources.

China has experienced the largest growth rates in PV manufacturing. From 2000 to 2012, the production has increased from 3 MW to 23,000 MW. This growth is the main reason for reduction in cost as well. In the same 12 year time span, the price has dropped from 45 RMB/W_p (~5.9 EUR/W_p) to 4.5 RMB/W_p (~0.59 EUR/W_p). The local industry in China has also had an impact on domestic use of Chinese PV cells. In 2012, the capacity was 23 GW, comprising 58% of the total global capacity. (Honghan, et al., 2014)

2.4.2 PV system scheme

The photovoltaic cells are combined together to form a solar panel. Currently most commercial panels are made from crystalline silicon cells. The panels are modular, which makes the system easy to upgrade. With battery backup systems such as the ones reviewed in this thesis, the electric current generated by the cells is stored in a battery. A charge controller controls the charge and load through regulation of electricity. The battery stores the electricity for night time, to be used for lighting and other loads. There are many different applications for solar panels in addition to the common solar home systems and micro grids. These can be, for example, portable lighting systems, water pumping equipment, refrigeration, rural telecommunication, and road and railway signalling. (Kamalapur & Udaykumar, 2011)

The future of PV cells is very promising. As mentioned earlier, the cost of cells is expected to continue reducing and the growth expectations for the cell industry are remarkable. Currently, the technological development is focused on two cell types: dye-sensitized solar cells and multi-junction solar cells. Fundamentally, these are very different types of solar cells. The dye-sensitized solar cell aims at low-cost production, leaving the efficiency of the cell low, whereas the multi-junction cells are designed for maximum efficiency with high production costs. (Korpela, 2013)

The advantages and disadvantages of PV systems in electricity production are shown in table 2.6. It can be seen that PV is a potential alternative to consider in rural electrification projects where most of its disadvantages can be neglected.

Table 2.6. *Advantages and disadvantages of PV systems (Kamalapur & Udaykumar, 2011).*

Advantages	**Disadvantages**
Environmentally friendly (no emissions)	High capital cost
Easy transportation, assembly and installation in rural areas	Few types of devices can be operated with PV electricity (low power output)
Produces DC electricity to be stored in batteries	Higher potential of these systems is mainly in remote areas where grid extension is not cost effective
Does not need fuel	Not suitable for large loads
Noise free	
Low maintenance cost	
Every kWh of solar PV prevents the release of around 0.7 kg of carbon dioxide	

2.4.3 Physical background

Semiconductors are the key to modern day cell technology. The most common cell technology used is silicon cell that consists of n- and p-type semiconductors. The n-type semiconductor has a small amount of excess free electrons and the p-type semiconductor a deficit of free electrons. When these two layers of semiconductors are combined, it creates a p-n junction between them. This is essentially an electric field that separates positively and negatively charged electrons. Light consists of small particles called photons. These photons have energy that is transferred to electrons in the material. This affects the electrons and they start moving creating electric current. (Boyle, 2004)

Light has both particle nature and a wave nature. This is called wave-particle duality, which exists in electromagnetic radiation. The radiation intensity that comes from sun to earth (g_m) can be solved from equation (6)

$$g_m = \frac{A_a}{A_m} * g_a \ , \qquad (6)$$

where g_a is radiation intensity of the sun, and A_a and A_m are the area of sun and earth, respectively. (Boyle, 2004) Typical values for radiation intensity in Nepal are between 700 and 910 W/m^2. This radiation intensity, commonly known as solar radiation, is the most important variable needed in the study of solar energy.

Solar radiation changes depending on the angle at which the sun shines, cloudiness, altitude, pollution, and humidity. The radiation that enters the earth's atmosphere is absorbed and scattered by aerosols, clouds, and air molecules (Kamalapur & Udaykumar, 2011). This has direct impact on the radiation intensity absorbed by the cell. Air mass (AM) is a physical quantity defined as the quotient of the distance travelled by the solar radiation in the atmosphere of the earth and the thickness of the atmosphere on earth. This quantity is shown in equation (7) below

$$AM = \frac{SO}{ZO} = \frac{SO}{SO\cos\theta} = \frac{1}{\cos\theta}, \qquad (7)$$

with the variables shown in figure 2.8.

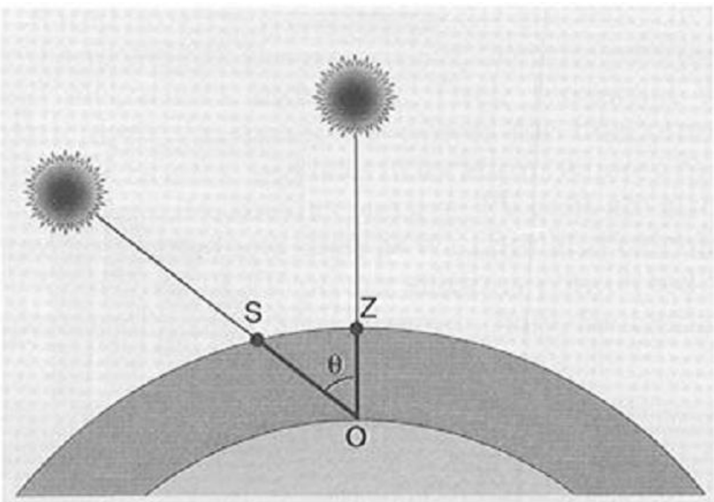

Figure 2.8. *The definition of air mass (Korpela, 2013).*

Standardised conditions are applied to assist the measurement of different PV cells together. The air-mass ratio in standard conditions is 1.5, which means an angle of 48 degrees. Other physical quantities that affect the cell performance are the temperature of the cell (25°C) and the solar radiation (1,000 W/m^2). The study of solar radiation is the cornerstone in designing and predicting the performance of solar PV cells. (Korpela, 2013)

The efficiency of a commercial solar cell is somewhere between 15-20%. It can be derived from the equation (8)

$$\eta = \frac{P_{max}}{G * A_{cell}} = \frac{f_p V_{oc} I_{sc}}{G * A_{cell}}, \tag{8}$$

where P_{max} is the maximum cell output, G is the solar radiation, and A_{cell} is the cell area. The maximum output of the solar cell can be derived from the product of short circuit current, open-circuit voltage, and bulk factor. Solar cell needs a control system to work with maximum efficiency as the maximum power changes according to working conditions. The theoretical efficiency maximum for solar cell is approximately 44%. This is because of imperfect absorption of the photons in the cell, which also includes the reflection of photons. The excess energy of the photons transforms into heat in the cell. In addition, the movement of electrons affects the efficiency by transforming a part of the electrical energy into heat. (Korpela, 2013)

Solar radiation and the temperature of the cell are the most important working conditions that affect the performance of the cell. The temperature of the cell is typically somewhere between -30 and 70 degrees of Celsius. When the temperature rises, the open-circuit voltage decreases and the short-circuit current slightly increases. These changes have a minor effect on the energy production. However, the most important factor affecting the energy production is the almost linear dependence of short-circuit current and radiation intensity. This is illustrated in figure 2.9 in which the lower situation has double radiation intensity compared to the upper situation.

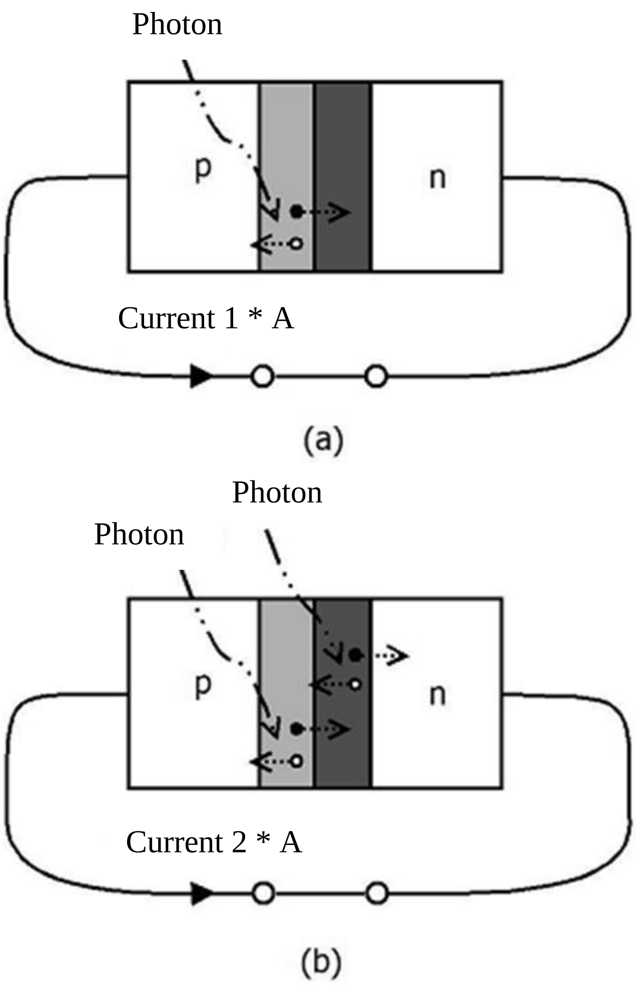

Figure 2.9. *Radiation intensity and short-circuit current (Korpela, 2013).*

It can be seen that as the radiation intensity doubles, the short-circuit current also doubles. (Korpela, 2013)

2.4.4 Cost estimation

Evaluation of the energy production of the solar PV systems and their cost is important. This can be done by analysing the radiation intensity in the site area in question. Energy production of a PV system varies greatly with weather conditions. The measurements made in Finland showed that partly cloudy days can reduce the energy production by 38% as compared to a sunny day. (Korpela, 2013)

The annual average for solar radiation in Nepal is 4.7 kWh/m^2/day, however, the terrain and weather change according to season and around the country. Tables 2.7 and 2.8, based on a study by Poudyal et al. (2011) show the different conditions in the country. It can be seen that weather conditions, altitude, and pollution affect solar radiation

Table 2.7. *Different conditions around Nepal (Poudyal, et al., 2011).*

City	Elevation (m)	Temperature Summer/winter	Special condition	11.2.2010 maximum solar radiation (W/m^2)	Daily variation of solar energy (MJ/m^2) (January)
Biratnagar	72	40/15	Tropical	704.51	2.49-14.39
Pokhara	800	30/8	High precipitation 4000 mm	815.97	6.95-16.22
Kathmandu	1350	29/7	High air pollution	777.27	10.45-15.75
Lukla	2850	16/-4	High altitude	914.03	6.76-18.97

Table 2.8. *Different conditions around Nepal (Poudyal, et al., 2011).*

City	Average daily solar energy (January)	Cloud transmittance factor (26.1.2010)	Seasonal variation winter/spring (MJ/m^2/day)	Seasonal variation summer/autumn (MJ/m^2/day)
Biratnagar	9.13	47.67	11.68/19.47	21.49/18.68
Pokhara	14.32	53.31	13.29/22.83	24.32/17.94
Kathmandu	13.71	52.98	13.00/20.86	24.76/15.48
Lukla	15.43	70.61	16.24/23.44	14.96/10.22

To evaluate the energy production estimates, precise radiation intensity data is needed for the site in question. The longer the measurement time for the data, the more accurate the results. The upper limit for energy production per day can be calculated from daily radiation intensity data. Figure 2.10 depicts the radiation intensity of Tampere, Finland, on a cloudless sunny day in August 2008.

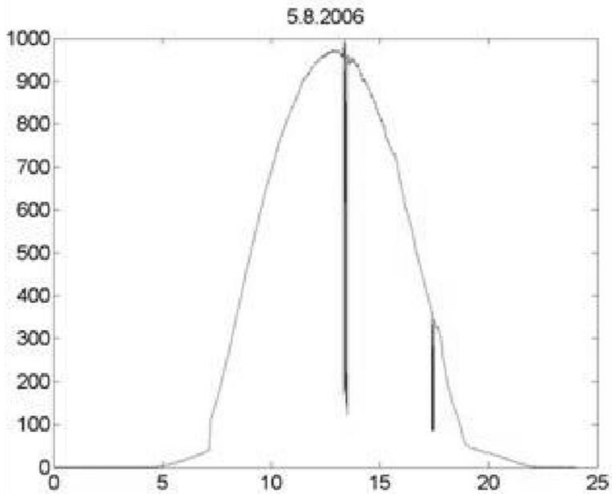

Figure 2.10. *Radiation intensity (y-axis W/m^2) curve during the day (x-axis h) in 5.8.2010, Tampere, Finland (Korpela, 2013).*

The energy production can be derived as the area beneath the curve, which in this case is approximately 6.5 times the nominal output power of the system. With a 100 kW system, this would mean lossless energy production of 650 kWh. The sudden vertical lines in the figure are clouds, which affect the radiation intensity. (Korpela, 2013)

A study from India reviewed a rural electrification project in which the PV system was designed to provide every household 100 W of loads for six hours per day. The total cost of this project was 8.4 USD/W (~6.7 EUR/W), including supply, installation, insurance, five years of comprehensive maintenance, and construction of the control room. There were also unexpected expenditures due to the rural nature of this project; the extra transportation costs were 6% of the total costs. (Loka, et al., 2013) This is important to note when evaluating the total system costs for Nepal as it also has a very rough terrain.

2.4.5 Solar potential in Nepal

Nepal is located close to the tropic of Cancer, thus it receives generous quantities of solar radiation. The average daily radiation varies between 3.6 and 6.2 kWh/m^2/d and there are approximately 300 sunny days in a year. The sun shines for about 6.8 hours per day with average radiation of 4.7 kWh/m^2/d. These figures are favourable for solar electricity production and it has been estimated that Nepal has around 2,100 MW of commercial potential for grid connected solar power. This is about twice the current electricity demand. (Water and Energy Commission Secretariat, 2010)

Solar electricity is a more flexible alternative for rural electrification as compared to micro hydro as it does not need specific topographical conditions. The most common use of solar electricity is a stand-alone solar home system (SHS), designed to provide electricity for a very small load. The system is illustrated later on in figure 3.7. From the early 1990s the use of SHS has become popular with over 115,000 installations by 2007, and with total power of about 3.5 MW$_p$. (Bhandari & Stadler, 2011) These systems are very popular because of their simplicity and low initial cost as pointed out by Saroj Rai in his study on solar home systems in Nepal (Rai, 2004). SHS systems work well in rural

Nepal because they are easy to install, simple to construct, have low voltage for safe usage, can be carried by hand for long distances, are cheap in initial cost, easy to upgrade, and durable. In addition, the use of SHS has already triggered a number of local enterprises that work with installation, distribution, management and maintenance of the system. There is a lot of growth potential in the market for SHS and centralized solar production as the majority of rural population still lack electricity.

The government of Nepal is currently supporting the use of SHS by provision of subsidies. These subsidies vary depending on the remoteness of the location and the capacity of the installed SHS. The subsidy tariff is divided into three categories according to remoteness and into two according to capacity. The subsidy ranges from 5,000 NPR (~41 EUR) to 10,000 NPR (~81 EUR), which accounts for approximately half of the total cost of a 20 W system. (Analysis by Solar Energy Component, AEPC/ESAP, 2011)

2.4.6 Review of built off-grid PV systems in developing countries

The electrification of rural villages that lack grid connection is often done by solar PV systems. The installation is normally either a single home system, with a power output of around 100 watts, or a centralized solar PV system with output in the kW range and a micro grid connecting it to surrounding houses and public buildings.

A typical micro grid scheme consist of PV cells, batteries, a power supply centre, connections, and transmission line to the end users. A rural electrification project in India powered 57 villages with centralized solar PV production of 365 kW_p. These villages had 2,225 houses and the power per house was 164 watts. In this case, the total levelized cost of electricity was 0.63 USD/kWh (~0.50 EUR/kWh), which was much lower than the analysed cost of electricity produced by diesel generators (1.35 USD/kWh or ~1.1 EUR/kWh). The electricity generated was designed for lighting (2*18 W) and a very low load of 60 W in a socket. This could be used for charging cell phones, fans to cool the air, and even small televisions. The power was available for 6 hours a day from 18:00 to 22:00 and from 04:00 to 06:00. A review of the project revealed that the residents were very open-minded towards electricity and they were soon wishing for greater capacity throughout the night. The installation of the equipment was rapid, taking only a few days per village, when most of the components were pre-fabricated. The PV system was shown to provide electricity for half the cost of diesel. The biggest challenges were logistical due to the rural nature of the project. Most of the sites were situated 20 to 50 km from main access points and did not have any roads. All the equipment had to be carried manually to the site (figure 2.11), which was difficult due to the weight and the size of the equipment (solar panels, mounting structures, batteries etc.). (Loka, et al., 2013)

Figure 2.11. *Manual transportation of the panels cross-country (Loka, et al., 2013).*

The above-mentioned study concluded that the main goal of a rural electrification project is successful and cost-contained energy supply that also enables economic and cultural benefits. This can be achieved by engaging the local stakeholders, introducing a simple payment structure, using simple equipment that have a high level of modularity, using locals for operation and management, and allowing for growth for future demand. (Loka, et al., 2013)

Multiple studies have reviewed SHS systems in developing countries. These studies show that the levelized cost of electricity produced by SHS systems is usually around 0.25 USD/kWh (~0.20 EUR/kWh). This excludes subsidies that are often granted for SHS, which means that the final cost is lower than 0.25 USD/kWh. The levelized cost of electricity is much lower for SHS than micro grid, which indicates that SHS is a better alternative for low load factors. Comparison of SHS and diesel generators shows that the cost of electricity is much lower with SHS and the farther the village from the nearest diesel station, the greater the difference. In a setting similar to Nepal, it was seen that SHS systems can supply electricity in a reliable manner throughout the year for small household loads. However, if there is need for higher load it is concluded that a supporting power source needs to be built to enable reliable and cost effective power supply. SHS systems in off-grid electrification projects consists of the panel itself, control unit, storage device, and dc/ac inverter. These installations are simple and require minimal maintenance. This is important in rural electrification as the users have low level of education and are not used to dealing with modern technology. (Loka, et al., 2013)

3 RESEARCH METHOD AND MATERIALS

The analysis of micro hydro and PV technologies is based on obtaining the levelized cost of electricity (LCOE) for the three technologies in question. LCOE is the annual discounted expenses (NPR) divided by the annual electricity production (kWh). This is a popular method for comparing different energy production technologies and is well suited for this thesis. The information required for the calculation of LCOE includes the costs of capital (discount rate 12%, plant lifetime 15 years for hydro and 20 for PV cell), operation and maintenance, financing, fuel (which can be neglected in this thesis), and utilization rate for each plant type. (U.S. Energy Information Administration, 2014)

Different methods were used to process the available data of RVWRMP for the calculation of LCOE. These include calculating the capital recovery factors (CRF) for various lifetimes of components and power plants, calculating depreciation based on the CRF values, and generating LCOE values based on trend line equations. CRF is calculated as shown in equation (9) below

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{9}$$

where *i* represents the discount rate and *n* represents the lifetime of the plant/component.

3.1 Micro hydro

The micro hydro research is based on literature review and values obtained from the RVWRMP micro hydro projects. The research focuses on the cost of electricity per kWh produced and load factor. The levelized cost of electricity (LCOE) enables easy comparison of RVWRMP's micro hydros with other similar projects presented in literature. The load factor indicates electricity usage vs. maximum production rate, which is an important element of sustainability of a micro hydro plant. The current load factor data is imprecise since it is an evaluation based on rough assumptions of the consumption instead of measurements.

Most of the sites have information sheets available with all the necessary information needed to calculate the LCOE and load factor. However, information of some plants is missing due to various reasons, the most common one being that the scheme is still under implementation. This means that the load factor, for example, cannot be calculated. It is also important to note that some schemes are lacking realized project costs, which means that the calculations for the LCOE are based on estimates. Another reason for missing key information is that RVWRMP is only funding these projects while the actual implementation of the projects is supported by AEPC. This thesis utilizes all available information to date. Seven out of 17 sites have been taken into account for further calculations due to incomplete project data.

The LCOE calculations performed had three different electricity consumption figures. These figures have also been used in the SHS and micro grid calculations to obtain comparable data. For the micro hydro, these figures were 126,100 kWh for the total average load (corresponding to approximately 40% load factor), 86,800 kWh (30% load factor) for the lighting only, and 60,700 kWh (20% load factor) for 70% of the lighting load. In addition to these, two extra cases were added to demonstrate the LCOE of a micro hydro plant that is working at 60% or 80% of its load. These were selected because they are an achievable goal even though the latter is unlikely in the near future.

The goal of this study is to show how the already completed micro hydro plants compare with single home photovoltaic systems and photovoltaic micro grids. In addition to calculations and literature information, a questionnaire study was conducted in two VDCs with micro hydro to find out actual user experiences and the quality of service. The sites selected for the survey were Jadarigad MHP in Pouwagadhi VDC, Bajhang district, and Kashegad MHP in Chhatara VDC, Bajura district (figures 3.1 and 3.2).

Figure 3.1. *Jadarigad MHP 21 kW.*

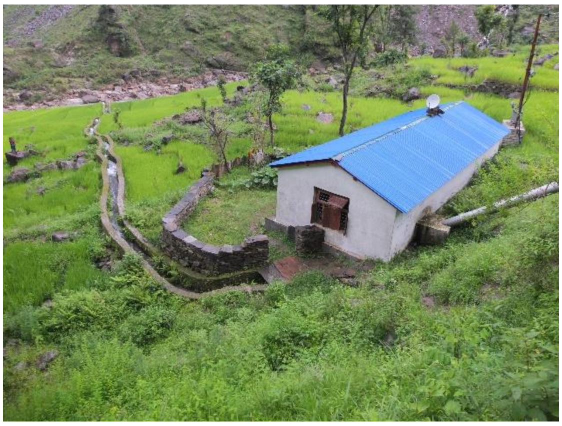

Figure 3.2. *Kashegad MHP 50 kW.*

The total number of questionnaires filled during the field visit was 127, 27 of which were filled in Jadarigad and 100 in Kashegad. The total beneficiary households in these sites were 245 and 677, respectively, to meet a minimum sample size of 10% of the households in each site for satisfactory sampling. The questionnaire focused on information regarding the effects of electricity on the rural life and electricity usage. The sampling was purposeful, including households that were interested in completing the survey.

3.1.1 Levelized cost of electricity and number of households

RVWRMP data was used to evaluate the change in LCOE when the number of households or the length of the distribution network was changed. The number of households reflects the village size, which affects the suitability of each electricity supply. The number of households changes the cost of electricity per produced kW in micro hydro schemes, which means that the larger the system in question, the more economical it is. Therefore, it is expected that micro hydro is the best alternative for larger systems (figure 3.3).

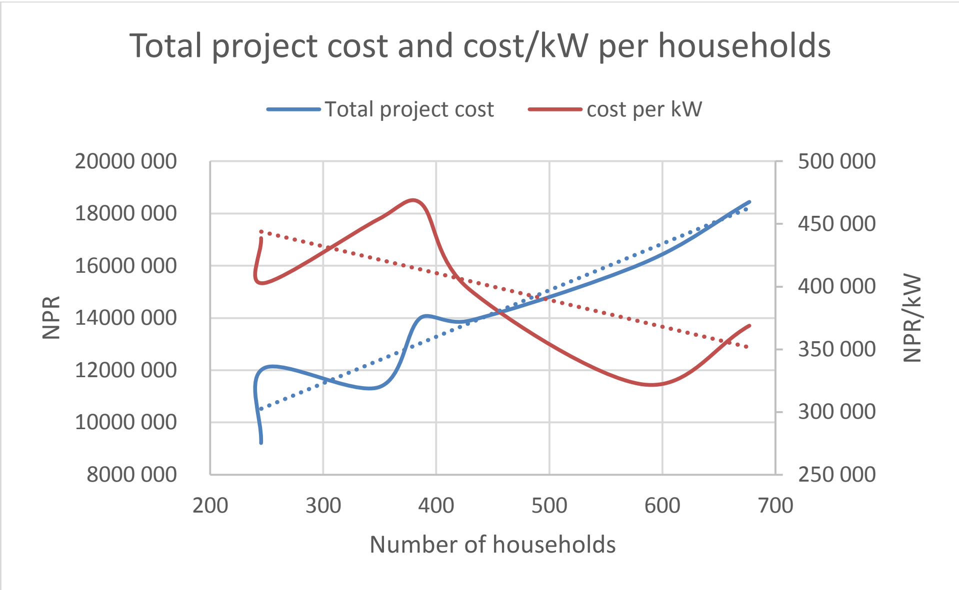

Figure 3.3. *Total project cost and cost per kW as a variable of household number (100000 NPR = 808 EUR).*

The data for figure 3.3 is presented in appendix 2 where the information of RVWRMP projects is listed. To help guide the decision making process of RVWRMP, it is important to know the number of households that makes micro hydro a preferred technology. The process of finding out the LCOE for the micro hydro plants of RVWRMP is illustrated in figure 3.4.

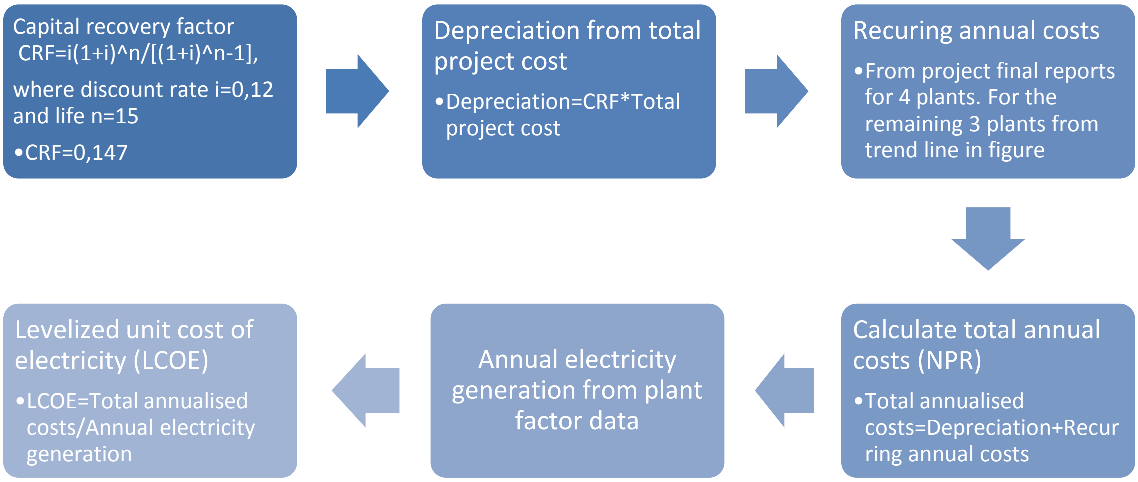

Figure 3.4. *Levelized unit cost of electricity calculation.*

The recurring costs vary depending on the power (kW) of the plant. This information was missing in three of the seven plants in question, but solved through simple plotting and a trend line (figure 3.5).

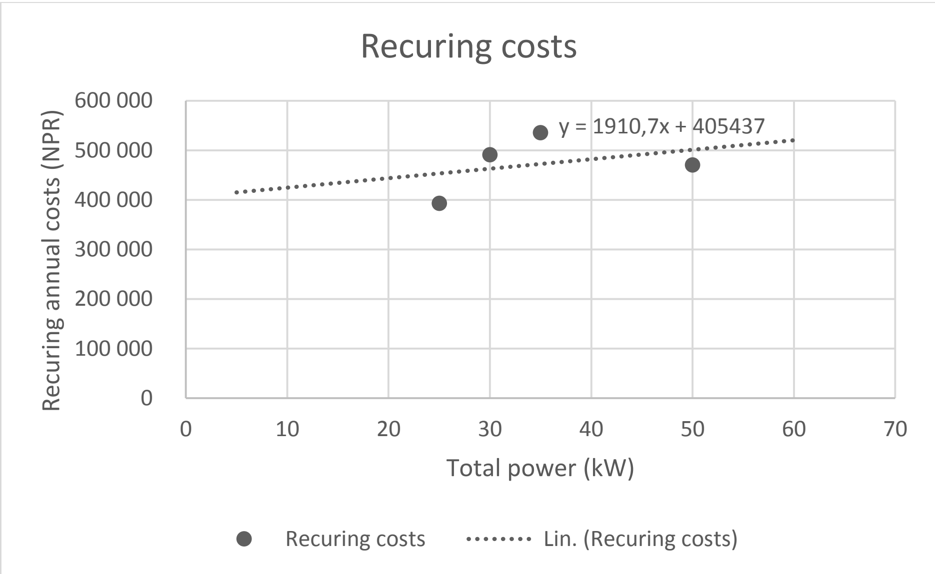

Figure 3.5. *Recurring costs of micro hydro plants (100,000 NPR = 808 EUR).*

In order to find out how the LCOE changes in case of differently sized villages, the previously obtained values were plotted and a trend line was added to obtain values for similar household numbers as with PV micro grids (figure 3.6).

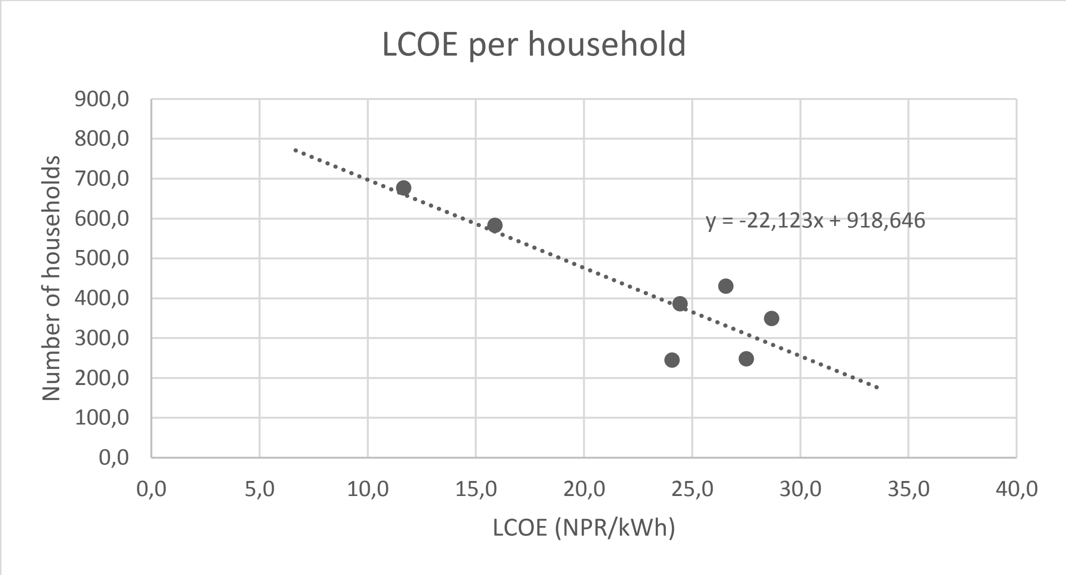

Figure 3.6. *The levelized cost of electricity per number of households (10 NPR=0.0808 EUR).*

It can be seen that the LCOE increases as the number of households decreases. The values from the trend line were further plotted together with the PV values for easy comparison of different electricity generation methods.

3.1.2 Levelized cost of electricity and the length of the power distribution network

LCOE was also used for the evaluation of the effect of the length of the power distribution network (PDN) on the overall economic performance of the plants. This was done by calculating the average power distribution network length and the cost of an average distribution network. Specific information of power distribution networks was available for three plants (Hoparigad, Kailash Khola V, and Maubheri Khola; table 3.1).

Table 3.1. *Power distribution network information (100,000 NPR = 808 EUR)*

	Unit	Hoparigad	Kailash Khola V	Maubheri Khola
PDN	km	34.97	7.594	14.03
Total cost	NPR	7,754,000	2,847,000	5,835,000
PDN cost	NPR/km	199,000	281,000	324,000
Number of HH		583	349	386
PDN/HH	km/HH	0.06000	0.0218	0.0394
Avg. PDN cost	NPR/km	268,100		
Avg. PDN	km	18.9		

Table 3.1. shows that the power distribution network length varies greatly between villages, and almost the same number of households may require double the amount of distribution line. A more detailed information on power distribution network cost calculations can be found in appendix 3. The power distribution network used in the calculations is a combination of a three-phase wire, used in the main grid, and a single-phase wire, used in household connections. The average power distribution network cost per km of transmission line is an estimate of the building cost for transmission line in the hills and mountains of Nepal.

The cost of the power distribution line is used to evaluate the effect of scatterdness on the LCOE by generating values for an average size village(table 3.2).

Table 3.2. *Average RVWRMP village (100,000 NPR = 808 EUR).*

Component	Unit	Average(W/O PDN)
Total power	kW	44.85
Total cost	NPR	9,038,000
Cost per kW	NPR	201,500
Depreciation (NPR)	NPR	1,327,000
Recuring annual costs (NPR)	NPR	471,200
Total annualised costs	NPR	1,798,000
Annual electricity generation kWh	kWh	126,100
LCOE (Levelised cost of electricity)	NPR/kWh	14.26
Number of households		417

These values are used to generate the LCOE values for villages with transmission line length of 1 to 49 km with one km intervals. The values obtained are then plotted together with values from PV micro grid and SHS values (see results).

3.2 Photovoltaic

The data for photovoltaic SHS and micro grids is based on literature. Battery size and module capacity are calculated for three SHS scenarios and three micro grid scenarios. The three SHS calculations are based on the average total electricity consumption in RVWRMP (40% load factor), average consumption used for lighting only (30% load factor) and 70% of average consumption used for lighting (20% load factor). The consumption figures for the calculations given in table 3.3 and at the end of appendix 1. Micro grid had three scenarios with three different loads similar to those of SHS (40%, 30%, and 20% load factor).

A. Chaurey and T. C. Kandpal of India introduced the calculation method for PV capacity and battery size. Their method is based on identical situations for SHS and micro grids with same number of households and same kind of electricity services. (Chaurey & Kandpal, 2010) This calculation method is good for obtaining the LCOE values for comparison of micro hydro and photovoltaic installations, which is why it was selected for this thesis.

The SHS used in this thesis, a simplification of the actual situation, is illustrated in figure 3.7. Comparing the below system with a micro grid, it can be seen that there are more solar panels, charge controllers, batteries and inverters in a micro grid, which is why the system is constructed differently. Micro grid photovoltaic systems usually consist of ground mounted panels and an operating building (figure 3.8). All of the information used for the calculation of SHS and micro grid levelized cost of electricity can be found in appendix 4.

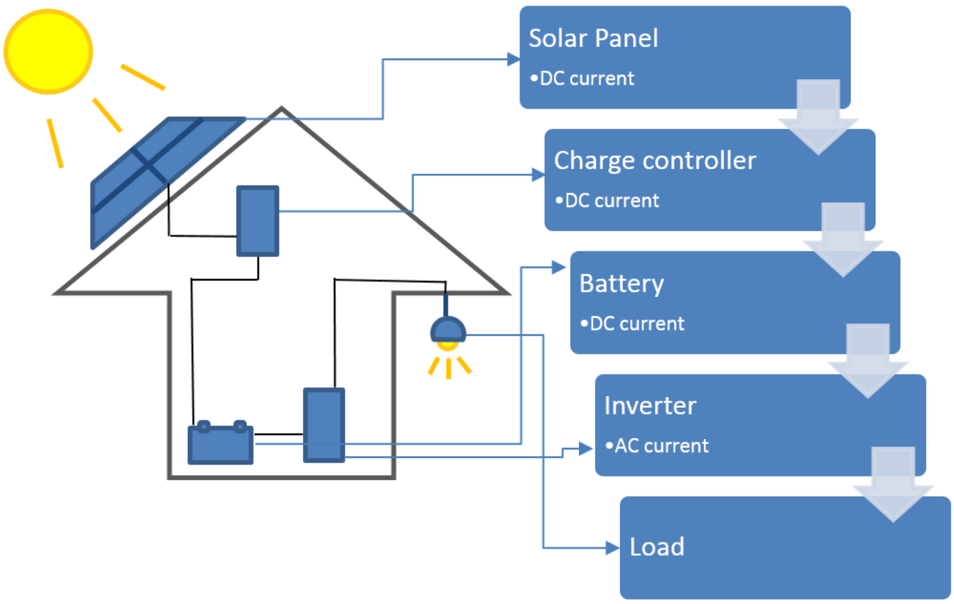

Figure 3.7. *Single home system.*

Figure 3.8. *Ground mounted PV system with power house (Bray, 2010).*

3.2.1 Levelized cost of electricity for single household systems

The calculation process started with an evaluation of the current PV equipment price trends in Nepal. It was important to have the latest PV equipment price of 2014 for Nepal because the technology is developing quickly. Due to lack of reliable statistical data, it was decided that the most reliable way to obtain the information was to use information available from the Indian PV market. These countries have a long history of trade and the currency of Nepal is tied to the currency of India, which means that the Indian PV prices can be directly converted into Nepalese currency without significant error. However, it needs to be considered that the actual prices in Nepal will be somewhat higher due to the transportation costs. The transportation of PV equipment is taken into account in the calculations by assuming that it is roughly eight percent of the total cost. This value was obtained from RVWRMP data, and therefore we assume that the weight and size of the transportable equipment is roughly the same as in the case of micro hydro.

The process of deriving the LCOE for SHS begins with calculating the necessary PV cell power requirement and battery capacity requirement to correspond with a similar quality of service as in micro hydro. The total DC energy requirement per day for an average RVWRMP village is obtained from the electricity consumption charts (table 3.3). This table was compiled from energy consumption figures provided by RVWRMP. The figures are estimates of the actual consumption because the lighting load consumption is calculated assuming that all production capacity is used for seven hours in a day. This is an optimal case, but according to the user survey, the loads of the households vary from mere 15 watts to 1,200 watts. Households that have appliances with higher power requirement, e.g. a rice cooker or water boiler, usually use them only for about an hour per day. Majority of the users require power less than 100 watts. Thus the real load factor will be lower than the one in table 3.3.

Table 3.3. *Monthly electricity consumption.*

Scheme Name	Lighting load (kWh/month)	End use (kWh/month)	Total consumption (kWh/month)	Total generation capacity (kWh/month)	Load factor (%)
Hoparigad	10,500	4,374	14,874	36,000	41 %
Upper Rilu	6,300	480	6,780	21,600	31 %
Jadarigad	4,410	1,815	6,225	15,120	41 %
Kashegad	10,500	12,420	22,920	36,000	64 %
Kailash Khola V	5,250	735	5,985	18,000	33 %
Kailash Khola IV	7,350	735	8,085	25,200	32 %
Maubheri Khola	6,300	2,386	8,686	21,600	40 %

After obtaining the information for the total energy consumption, the size of the battery is calculated for three days of autonomic service with battery efficiency of 85%. This means that the battery in both SHS and micro grid will be able to provide electricity continuously for three days with zero sunshine. The closest available battery size for SHS is 400 Ah, which is roughly seven times the size of a regular car battery, and it can run a 1,000 W load for 92 hours. The daily charge to be supplied is divided by the efficiency of the charge controller in order to obtain the charge to be supplied to the battery. After this the DC energy to be provided by the PV array is calculated from the result of the previous equation by multiplying it with the operating voltage of 12 V. The DC energy to be generated for providing the required value of the previous result is calculated by multiplying it with all the losses listed in table 3.4. The PV capacity requirement can be obtained from this value by dividing the previous result with the equivalent hours of full sunshine in Nepal. The exact numbers for SHS and micro grid with total average consumption are presented in table 3.4 on the next page.

The three scenarios were calculated for SHS to see how it would compare with micro hydro with various loads. The first calculation, also in the table above, had the average load of all the seven micro hydro plants from table 3.3. The second calculation contained the average lighting load and the third calculation contained 70% of the lighting load. The corresponding PV module requirements were 270 W_p, 185 W_p, and 130 W_p and battery capacities 400 Ah, 270 Ah, and 190 Ah.

Table 3.4. *SHS and micro grid capacity calculations.*

		SHS	Micro grid
Number of households		417	417
Diversity factor		1.00	1.10
Inverter efficiency		0.90	0.95
Total DC energy required per day	W	934	335,000
Operating voltage	V	12.00	120.00
Charge to be supplied every day	Ah	77.80	2,790
Battery efficiency		0.85	0.90
Charge to be given by battery per day	Ah	91.53	3,100
Maximum depth of discharge (MDOD)		0.70	0.70
Days of autonomy	d	3.00	3.00
Size of the battery	Ah	392	13,300
Nearest available battery size	Ah	400.00	13,300
Efficiency of charge controller		0.85	0.90
Charge to be supplied to battery per day	Ah	108	3,450
DC energy to be provided by the PV array	Wh	1,290	414,000
Loss of energy due to ambient temperature		0.10	0.10
Loss of energy due to dust etc.		0.10	0.10
Loss of energy due to mismatch among solar cells		0.15	0.10
DC energy to be generated for providing the required value	Wh	1,800	576,000
Equivalent hours of full sun-shine (EHFS)	h	6.80	6.80
PV requirement	W_p	264	84,700
PV requirement per household	W_p	264	203
PV module capacity for SHS	W_p	270	
Total PV capacity	W_p	113,000	84,700

The annual life cycle costs of the SHS scenarios were calculated using capital recovery factors for each component. The capital recovery factor helps to evaluate the annual costs of each component depending on its expected lifetime and the rate of interest. The interest rate used in this thesis was 12% while the lifetime of each component is given in table 3.5. The data is presented for the 280 W_p and 400 Ah SHS. The other two scenarios were calculated similarly with LCOE values of 29.18 NPR/kWh (~0.23 EUR/kWh) for the 185 W_p and 280 Ah SHS, and 30.14 NPR/kWh (~0.24 EUR/kWh) for the 130 W_p and 200 Ah plant.

Table 3.5. *LCOE calculation for SHS_1 (1,000 NPR = 8,08 EUR).*

Component	Capital cost (NPR)	Life (years)	CRF (fraction)	Annualised costs (NPR)
SHS_1				
Module_280 W_p	22,900	20	0.13	3,070
Battery_400Ah	50,610	8.5	0.19	9,822
Charge controller	4,150	5	0.28	1,151
Balance of systems	12,800	10	0.18	2,265
Transportation costs	16,300	20	0.13	2,180
Annual O&M costs				720.0
Total annualised costs	90,500			19,210
Annual electricity generation kWh				625.5
LCOE (Levelized cost of electricity)				30.71

The life of each component was obtained from the study by Chaurey & Kandpal (2010). The panel cost varies depending on the technology and the power output of the panel. The multicrystalline cell was used for calculations of this thesis. The current average price of this cell in India is 38 INR/W (~0.49 EUR/W) for a cell of 30-300 W (Bijli Bachao, 2014). The battery price was obtained from an online battery retailer in India by compiling information of the battery cost and their capacity. Twenty-eight different batteries were taken into account for the calculation of the average NPR/Ah for the batteries. The batteries were either tubular or flat plate batteries, both suitable for solar backup batteries. (Battery Bhai, 2014) The average battery price in India was 126.5 NPR/Ah (1,01 EUR/Ah).

The balance of system (BoS) costs represent all the system costs without the module, the battery and the charge controller. This means mounting and wiring equipment, installation, and an inverter. BoS costs have been assumed constant since 2012. This assumption is valid because the cost of this type of hardware has not changed much for the past few years. However, since the dramatic price drop in PV cells, the BoS costs have become more important since nowadays they account for approximately half of the system cost. (Calhoun, et al., 2014) The BoS and annual operations and maintenance costs have been derived from the study by Chaurey and Kandpal in 2010. Transportation costs, derived from RVWRMP data, are given in table 3.5.

3.2.2 Levelized cost of electricity for micro grid

Photovoltaic micro grid was selected as the best available alternative for renewable energy technology because it overcomes most of the negative features of SHS compared to micro hydro. The quality of service of micro hydro is excellent as it produces steady supply of electricity throughout the day. This is not the case with solar photovoltaics because the sun only shines a limited time per day, which is why a PV system needs an energy storage. Sometimes long periods of cloudy days lead to energy shortage due to limited sunshine. Another setback of solar PV is the need for a suitable inverter for electronic appliances to convert the DC electricity from the battery to an AC. Inverters also have a limited power output capacity, which means that some appliances cannot be properly used due to their high power requirement. SHS inverters are selected based on the desired power output, and they typically range from 200 W up to approximately 1,000 W. This kind of restriction does not apply to micro hydro or photovoltaic micro grid.

The LCOE of micro grid has been calculated as in the study by Chaurey and Kandpal (2010). First, the average cost of power distribution network in kilometres was derived from RVWRMP data (table 3.1) which shows that the average PDN cost is 268,100 NPR/km (~2,146 EUR/km). A benchmark value of 250,000 INR/kW_p (~3,232 EUR/kW_p) of a micro grid PV capacity has been given in the study by Chaurey and Kandpal. Since this value was from 2010 it had to be re-evaluated to match the price reduction of PV cells. PV cost of 51.2 NPR/W, similar to that of SHS, was used. The power-conditioning unit (PCU) consists of charge controllers, inverters, distribution boards, junction boxes, and wiring. The total cost of PCU per watt was 60.5 NPR (~0.48 EUR), approximately half of the cost of total micro grid. The PCU cost was derived from information provided by the Energy Alternatives India (2013). The battery cost, 126.5 NPR (~1.01 EUR) per Ah, was the same as in SHS. Transportation cost was calculated as in SHS, accounting for 8 percent of the total costs.

The calculation of the LCOE for micro grid was divided into three categories with different PV capacities similar to those in SHS. The first case demonstrates the current average load of micro hydro (40% load factor), for an average sized VDC in terms of household number and length of PDN. The second case demonstrates the current average load of micro hydro without profitable end-uses (30% load factor) with approximately 30 percent reduction in kWh consumption. The third case demonstrates the current average load of micro hydro similar to that in case two with the exception of an additional 30 percent reduction in the load (20% load factor). These categories can be found in table 3.6 on the next page. The third case was selected because the current method of calculation for energy consumption applied in RVWRMP assumes that the entire production capacity of each micro hydro plant is utilized for 7 hours a day. This is a coarse assumption and, in fact, the consumption is actually lower than the one currently projected.

PV and battery capacities were calculated for all three cases as shown earlier in table 3.4. After obtaining these figures, the calculation for LCOE began with calculating the overnight costs of various components. The overnight costs were transformed into annual expenses by multiplying the cost of components by their respected capital recovery factors (CRF). The capital recovery factors were calculated for each component assuming an interest rate of 12% and a component's life time as given in table 3.5. Operation and maintenance costs were derived from the study of Chaurey and Kandpal (2010) with a fixed value of 192,000 NPR (~1,537 EUR) per year. All annual expenses were added and divided by the total generation of electricity to produce the LCOE values (table 3.6).

Table 3.6. *The levelized cost of electricity of micro grid (1,000 NPR = 8.08 EUR).*

Item	Symbol	microgrid1_1	microgrid2_1	microgrid3_1
N.O. households		417	417	417
Lenght of PDN	km	19.4	19.4	19.4
PV cost	NPR/W	51.2	51.2	51.2
PCU cost	NPR/W	60.5	60.5	60.5
Battery capacity	Ah	13,300	9,160	6,410
Battery cost	NPR/Ah	126.5	126.5	126.5
PV capacity	kW_p	84.70	58.27	40.79
Cost of microgrid (W/O PDN)	NPR	11,140,000	7,665,000	5,366,000
Cost of PV	NPR	4,337,000	2,983,000	2,088,000
Cost of Battery	NPR	1,682,000	1,159,000	811,000
Cost of PCU	NPR	5,123,000	3,524,000	2,467,000
Cost of transporta-tion	NPR	1,388,000	1,110,000	925,900
Cost of PDN, SC	NPR	6,207,000	6,207,000	6,207,000
Total cost of mic-rogrid	NPR	18,740,000	13,870,000	11,570,000
NPR/kW_p of mic-rogrid	NPR/kW_p	221,200	238,100	283,700
C_opv*CRF	NPR	580,600	399,500	279,600
C_otra*CRF	NPR	185,800	148,600	124,000
C_obatt*CRF	NPR	326,600	205,200	143,600
C_opcu*CRF	NPR	994,100	623,800	436,700
C_opdn*CRF	NPR	1,204,000	1,099,000	1,099,000
Annualised capital cost	NPR	3,292,000	2,476,000	2,082,000
Annual O&M cost	NPR	192,000	192,000	192,000
Total annual cost	NPR	3,484,000	2,668,000	2,274,000
Annual energy ge-neration	kWh	189,200	130,200	91,120
Levelised unit cost of electricity	NPR/kWh	18.41	20.49	24.96

This procedure was used to calculate the LCOE of micro grid for different combinations of household size and power distribution network length to form graphs as mentioned in chapters 3.2.1 and 3.2.2. The first graph shows how the LCOE changes depending on the number of households when the power distribution network length changes according to the number of households. The second graph shows how the LCOE changes depending on the length of the power distribution network when the number of households stays the same.

3.3 Rural electricity usage

Rural electricity usage has been examined more thoroughly in the results chapter based on information retrieved during the field visit as well as some statistical information provided by the government of Nepal. This analysis is divided in two chapters that describe the typical electric appliances and the typical micro enterprises found in rural Nepal. The power consumption figures for each appliance and micro enterprise are provided in tables for ease of comparison. The power consumption for each appliance is obtained from ABS Alaskan tables and/or notes taken during the field visit. There is also information on the usability of the appliances with a small PV system. The utilization rate in the micro enterprises table describes an estimate of the time used with the electronic equipment powered on, compared to the total time spent working.

3.4 Environmental aspects

The environmental aspects of the three technologies in question were evaluated based on literature and experiences from the field visit. The environmental effects are described to highlight the characteristics of each system and to offer further information for the decision making process of RVWRMP. The direct impact on the environment is evaluated from multiple perspectives including greenhouse gas emissions, noise, wildlife, land use, and other environmental effects such as capacity increase and maintenance need. The direct impact does not include the environmental effects from the production of the equipment (solar panels, electro mechanical equipment etc.). It is important to consider that the production of solar panels requires some water and chemical toxics to purify the semiconductor surface.

4 RESULTS

The results are based on literature and calculations derived from the data of RVWRMP with focus on the comparison of LCOE of different electricity generation methods. The LCOE calculations were divided in two categories with three cases as presented earlier in chapter three. The categories were household number and the length of the power distribution network. The household number varied from 94 to 587, which represents the majority of the current VDCs of RVWRMP with micro hydro. The length of the distribution network varied from 2.5 to 48.9 km, which currently represents every VDC of RVWRMP with micro hydro. In addition to the LCOE calculations, a literature review reflects on the environmental effects of each technology and compares them against each other and diesel generators.

The micro grid has some advantages over SHS and in some cases over micro hydro, too. These advantages stem from modularity and the features of centralized power production of micro grid. However, this is not always the case as both the SHS and micro hydro have their own advantages over micro grid. The advantage of SHS over both micro grid and micro hydro is its simplicity and grid independency, but the biggest drawback is its limited power output. SHS inverters are typically in the range of 200 W to 1,000 W, which rules out the use of many household appliances. However, the SHS system needs to produce the required electrical energy based on daily consumption when in reality this consumption varies. This variation can be exploited by micro grid since not all the users can be expected to be connected at all times. Micro grid has a built-in diversity factor that is defined by Chaurey and Kandpal as the ratio of the sum of all individual peak loads to the average load. Other advantages of micro grid over SHS arise from higher efficiency batteries, charge controllers, and reduced losses of energy due to ambient temperature. (Chaurey & Kandpal, 2010) The main advantage of micro grid with battery backup over micro hydro is its modularity, which means that it can be designed to produce just enough energy for every VDC in question. In addition, when the power requirements grow, the production and storage capacity can be easily increased by adding more solar panels and batteries to the system to fulfil the requirements. Compared with the optimal micro hydro cases, however, they are by far the cheapest alternatives as can be seen from the figures later on. It is important to remember that each system has its benefits and the results presented later on highlight these benefits and help better to understand them.

4.1 LCOE and the household number

This chapter presents the levelized cost of electricity (LCOE) values of different power production technologies when the number of households changes. The required distribution line length is calculated from the household number according to the data of

RVWRMP, which indicates that the average distribution line length per household is approximately 46.6 meters. The LCOE of SHS installations does not change according to the household number because its cost is calculated for a single household and distribution network is not needed. As mentioned in chapter three, the cases evaluated in this thesis are as follow: average total consumption, average lighting consumption, and 70% of average lighting consumption.

The average total consumption describes the current case of RVWRMP's micro hydro VDCs with a **40% load factor**. The micro grid and SHS systems were calculated to fit exactly this consumption, which means that there is no extra production unlike in micro hydro. These LCOE values are presented in figure 4.1.

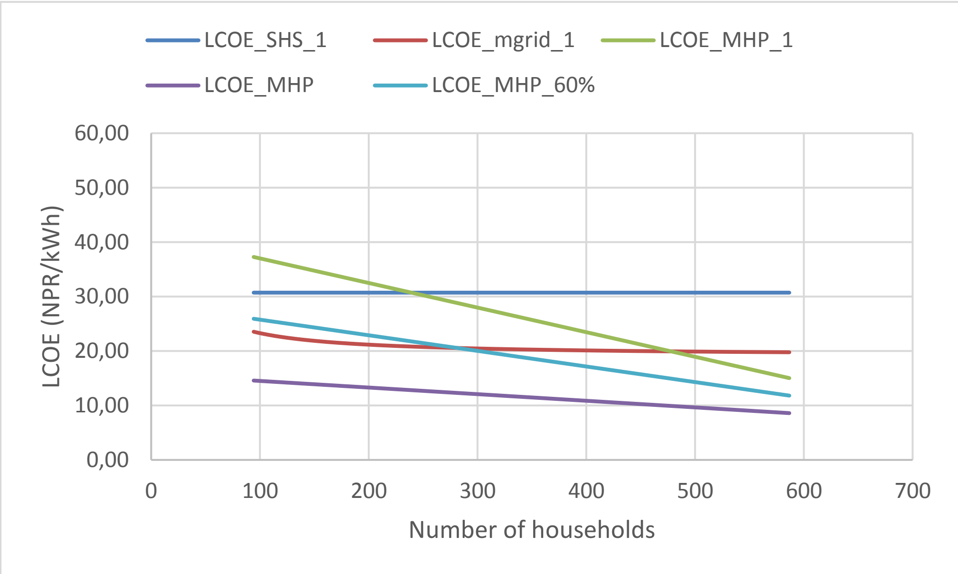

Figure 4.1. *LCOE and household number with average consumption (10 NPR = 0.0808 EUR).*

It can be seen that the current case favours the SHS and micro grid systems if the VDC is small. Micro hydro is a better alternative for SHS after 200-300 households and for micro grid after 400-500 households. The most cost efficient option would be a micro hydro plant with 80% load factor (LCOE_MHP) whereas a more realistic goal is the 60% load factor. These are illustrated to highlight the effect of load factor on the LCOE in micro hydro. The 80% load factor line can be found in each following figure.

The average lighting consumption describes a situation where micro hydro has a **30% load factor** and the PV systems have been calculated to match this electricity consumption. This case describes a situation where the micro hydro power is mainly used for electrifying household lights and there are no productive end-uses in the VDC. Thus the load factor drops ten percent (figure 4.2).

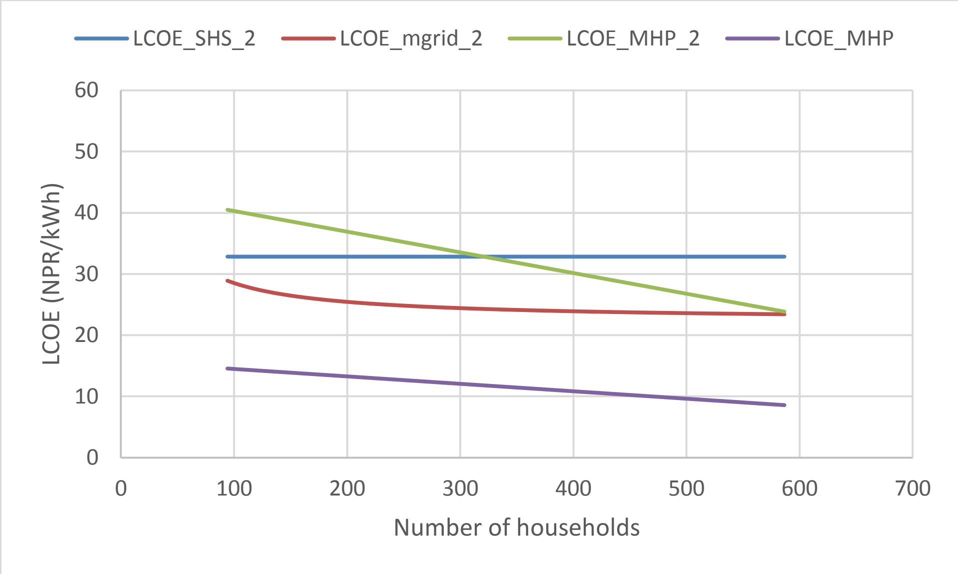

Figure 4.2 *LCOE and household number with average lighting consumption (10 NPR = 0.0808 EUR).*

It can be seen that the LCOE of SHS has risen to approximately 32.5 NPR/kWh (~0.26 EUR/kWh) and the LCOE of micro grid about four NPR/kWh (~0.032 EUR/kWh) throughout the graph. In addition, the micro hydro has risen even more by about five NPR/kWh (~0.040 EUR/kWh). This has led to increased usability of SHS and micro grid and an even bigger gap to reach the 80% load factor for micro hydro. In this case micro hydro is a better alternative to SHS when the number of households is below 300-400. With micro grid the same value is below 550-650.

The 70 percent of average lighting consumption describes a situation where micro hydro has **20% load factor**, and the PV systems have been calculated to match this consumption. The need for a reduced value of average lighting consumption stems from the fact that in reality not all lights are used for seven hours a day. This leads to an even worse situation for micro hydro compared to the PV systems (figure 4.3).

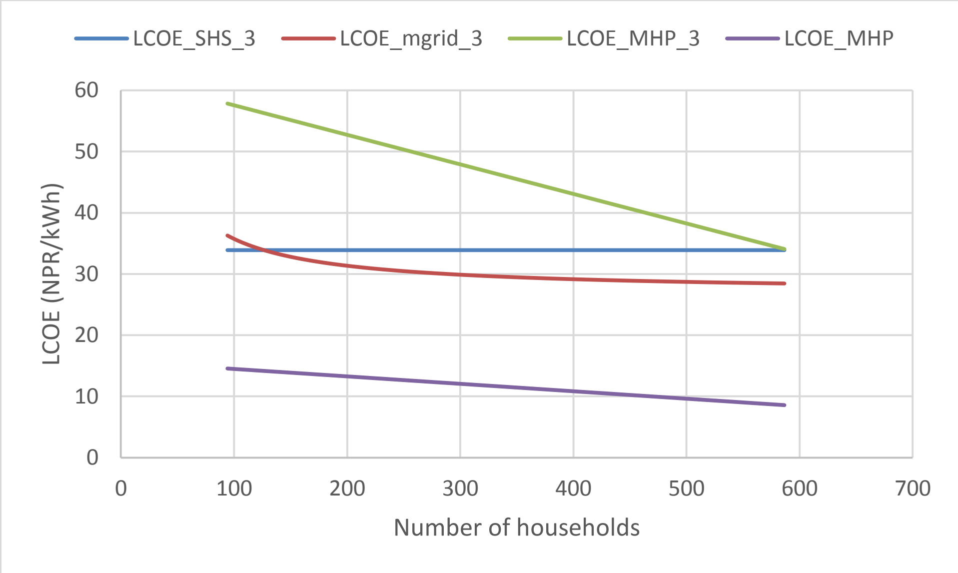

Figure 4.3. *LCOE and household number with 70% of the average lighting consumption (10 NPR = 0.0808 EUR).*

It can be seen that the SHS is a better option over micro hydro until the household number reaches over 600. For micro grid the same value is 600-700.

4.2 LCOE and the length of the power distribution network

This chapter presents the levelized cost of electricity (LCOE) in terms of the length of the power distribution network (PDN), which highlights the effect of scatteredness of households on the LCOE. This means that the household number stays the same while the PDN length changes. The number of households used is 417, which is the average size of a VDC. Again, the LCOE of SHS does not change as it does not require any grid connection. All of the cases presented are similar to those in the previous chapter.

The first case is presented in figure 4.4. It can be seen that the LCOE of micro grid and micro hydro rises when the length of the PDN increases.

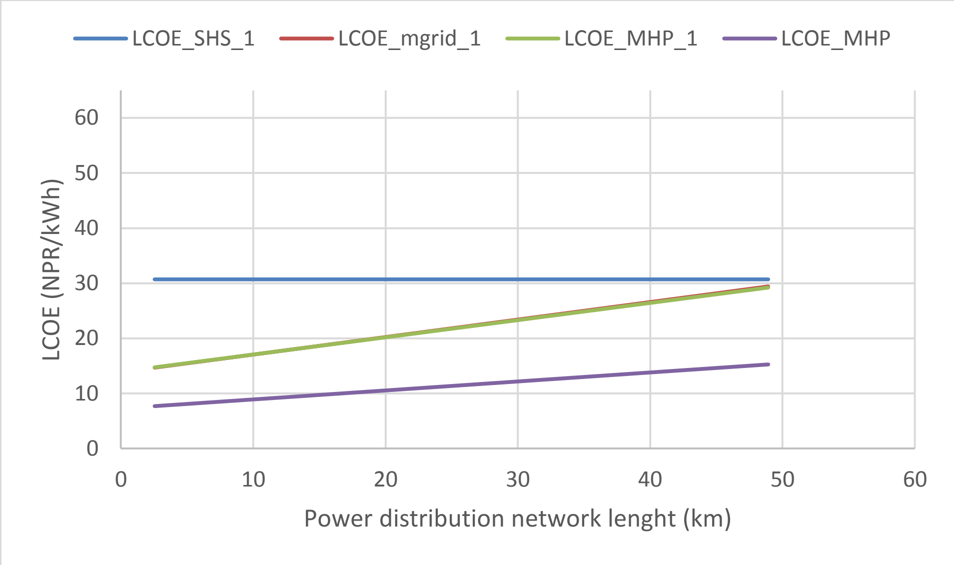

Figure 4.4. *LCOE and power distribution network length with average consumption (10 NPR = 0.0808 EUR).*

It is noteworthy that the mgrid_1 and MHP_1 lines have exactly the same slope. This is because the only variable affecting the LCOE is the added cost of building the grid. In addition, the cost of building the grid is assumed to be the same in both cases. With the average consumption, the micro grid and micro hydro are both valid options for power generation. The SHS systems can be neglected for an average sized VDC of 417 households until the PDN reaches about 50 km. The difference of LCOE as compared to the optimal 80% load factor of micro hydro is seven NPR/kWh (~0.056 EUR/kWh) with a growing trend the longer the PDN.

The second case highlights the LCOE with average lighting consumption (figure 4.5).

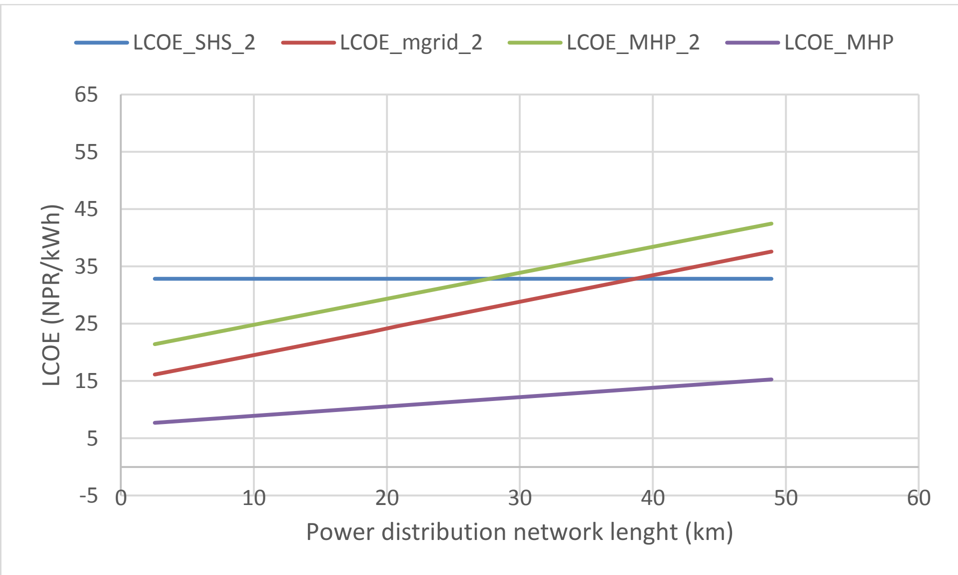

Figure 4.5. *LCOE and power distribution network length with average lighting consumption.*

It can be seen how the LCOE of micro hydro increases more rapidly than that of the micro grid and SHS. In this case, the SHS is a potential option after 40 km of PDN whereas the micro grid is the best option for a shorter PDN.

The third case presents the situation where the average lighting consumption is decreased by 30 percent (figure 4.6).

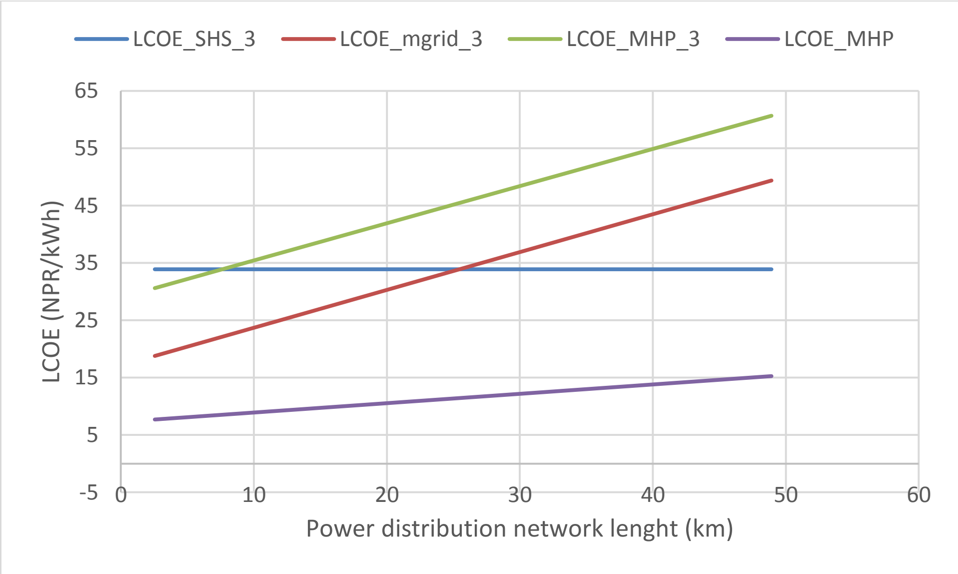

Figure 4.6. *LCOE and power distribution network length with 70% average lighting consumption.*

It can be seen that SHS is the best alternative when the power distribution network length exceeds 25 km. The LCOE of micro hydro continues to grow while the micro grid is also growing, but more slowly. The micro grid is the best alternative for a power distribution network length less than 25 km in length.

4.3 The main results

The main results of the calculations are summarized in tables 4.1 and 4.2 indicating the point when micro hydro becomes a better option to either SHS or micro grid.

Table 4.1. *The favourability of micro hydro against SHS.*

Load Factor	Micro hydro HH	Micro hydro PDN
20%	>590	<7
30%	>320	<27
40%	>240	<49
60%	Better	Better
80%	Better	Better

It can be seen that the higher the load factor the less households or PDN network are needed for micro hydro to become the best alternative. The definitions *worse*, *same* or *better* apply for the entire scale of either households or PDN length. The *less or greater than* characters apply for the corresponding set of values.

Table 4.2. *The favourability of micro hydro against micro grid.*

Load Factor	Micro hydro HH	Micro hydro PDN
20%	Worse	Worse
30%	>590	Worse
40%	>480	Same
60%	>290	Better
80%	Better	Better

In table 4.1, for example, micro hydro is favoured at 40% load factor when the household number is greater than 240.

4.3.1 SHS against MHP

When the information of figures 4.1 and 4.4 is combined, another figure highlighting the working parameters of SHS can be generated (figure 4.7).

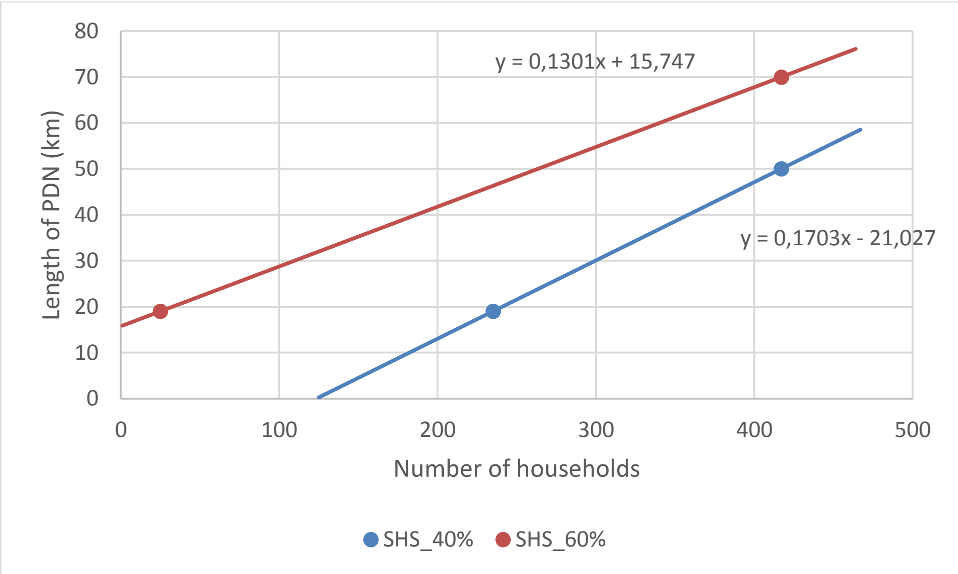

Figure 4.7. *Working parameters of SHS for 40% and 60% capacity factor.*

The two points in the graph are taken from the previously mentioned figures and represent the values at which the SHS becomes a better option to micro hydro. The area above the line represents the working parameters at which the SHS is better while the area beneath the line represents the working parameters at which the micro hydro is better. The SHS2 represents the higher than average capacity factor and, as can be seen, the red line is considerably higher than the blue line.

To understand and use the information in figure 4.7 more easily, simple equations (10 and 11) have been added. These equations show which of the technologies has the best economic performance. They can be used for every village as long as the number of households to be electrified and the length of the PDN are known.

$$f_{SHS/MHP\_40\%} = 0{,}17 * HH - PDN_{km} - 21 \qquad (10)$$

$$f_{SHS/MHP\_60\%} = 0{,}13 * HH - PDN_{km} - 16, \qquad (11)$$

where the HH represents the number of households and PDN_{km} represents the length of the power distribution network in kilometres. These equations assist in the selection of technology. If the answer is negative, SHS is better. If it is positive, micro hydro is better. The closer the answer is to zero, the closer the two technologies are economically. Equation number 11 describes a situation with 40% capacity factor and equation number 12 a situation with 60% capacity factor.

4.3.2 Micro grid and SHS

The characteristics of micro grid offer certain advantages over SHS as discussed earlier. Looking at these characteristics more closely (table 3.4), it can be seen that the total PV capacity needed is approximately 25 percent less in the case of micro grid. The main variables affecting this are the operating voltage of the battery and more efficient batteries, inverters, and charge controllers.

The reduced need for PV equipment in micro grid offers cost savings while maintaining a solid service quality. Micro grids are designed to produce electricity with similar capabilities as micro hydro, but the length of the PDN affects their LCOE. This means that the savings from the reduced need for PV equipment will gradually diminish as the power distribution network grows (figures 4.4 to 4.6.)

4.4 The questionnaire

The short questionnaire survey, conducted during the field visit to Chhatara and Pouwagadhi VDCs, gives an insight on current electricity situation in micro hydro powered villages in rural Nepal. The overall experience among the users was happiness and satisfaction with the electricity services produced by micro hydro. The availability of electricity was mostly good, and the employees of the power plants were highly respected for their work.

The average power required per household was 130 watts in Pouwagadhi and 182 watts in Chhatara (figure 4.7) although the power requirement of some households rises far beyond the average. This is caused by the use of water boilers, rice cookers and electronic devices by wealthier households.

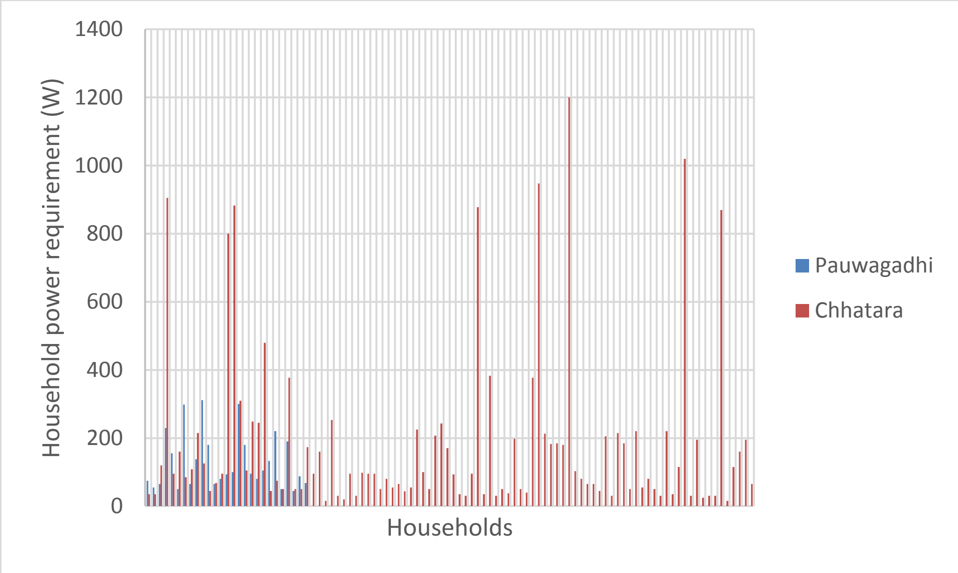

Figure 4.8. *Power requirement of households in Pouwagadhi (blue) and Chhatara (red).*

Due to the low load factor of an average micro hydro plant, it would be beneficial if more electric appliances were used in the low load times.

Information related to the use of electricity in the two VDCs visited is presented in table 4.3.

Table 4.3. *Pouwagadhi and Chhatara VDC information.*

Item	Pouwagadhi	Chhatara	Unit
Av. Power requirement	130.1	181.5	W
Av. Number of residents	6.6	6.6	
Number of lights	5.9	4.8	
Number of TV	0.3	0.3	
Number of radio	0.3	0.3	
Number of mobile phones	1.6	1.8	
Years with electricity	4.0	3.0	a
Number of students in household	3.0	3.3	
Does your household use electricity for income generating activities (YES/NO)	44.4	13.0	% of YES
Have you considered buying more capacity (YES/NO)	63.0	48.0	% of YES
Has someone from your household been employed in enterprises that use MHP electricity? (YES/NO)	44.4	10.0	% of YES

It can be seen that the number of household members is similar in both VDCs and that approximately every third household has its own television and radio in both VDCs.

Pouwagadhi micro hydro plant has been in operation for four years and the Chhatara micro hydro plant for three years. It can be seen that more households are involved in income generating activities through micro hydro in Pouwagadhi where more households have also considered buying more capacity.

A summary of the user satisfaction and experiences was measured by the questions presented in table 4.2 and responses illustrated in figure 4.9.

Table 4.4. *User satisfaction and experiences of micro hydro.*

Nr	Question	Level of agreement by respondents*				
		1	**2**	**3**	**4**	**5**
1	Are you satisfied with the availability of electricity	0%	1%	6%	13%	81%
2	Are you satisfied with the cost of electricity	0%	0%	6%	24%	70%
3	Do you feel like electricity has had a positive effect on your households general quality of life	0%	2%	9%	31%	58%
4	Do you feel like electricity has had a positive effect on your households education level	0%	1%	9%	22%	69%
5	Do you feel like electricity has had a positive effect on your households information level	0%	6%	15%	13%	66%
6	Do you feel like electricity has had a positive effect on your households communication level	0%	4%	13%	28%	55%
7	Do you feel like electricity has had a positive effect on your households general health	1%	2%	13%	43%	41%
8	Do you feel like electricity has had a positive effect on empowering the female population of your household	1%	2%	27%	37%	33%

* Number 1 = completely not agree; number 5 = fully agree; numbers 2, 3 and 4 represent partial agreement/disagreement when equally divided in fifths.

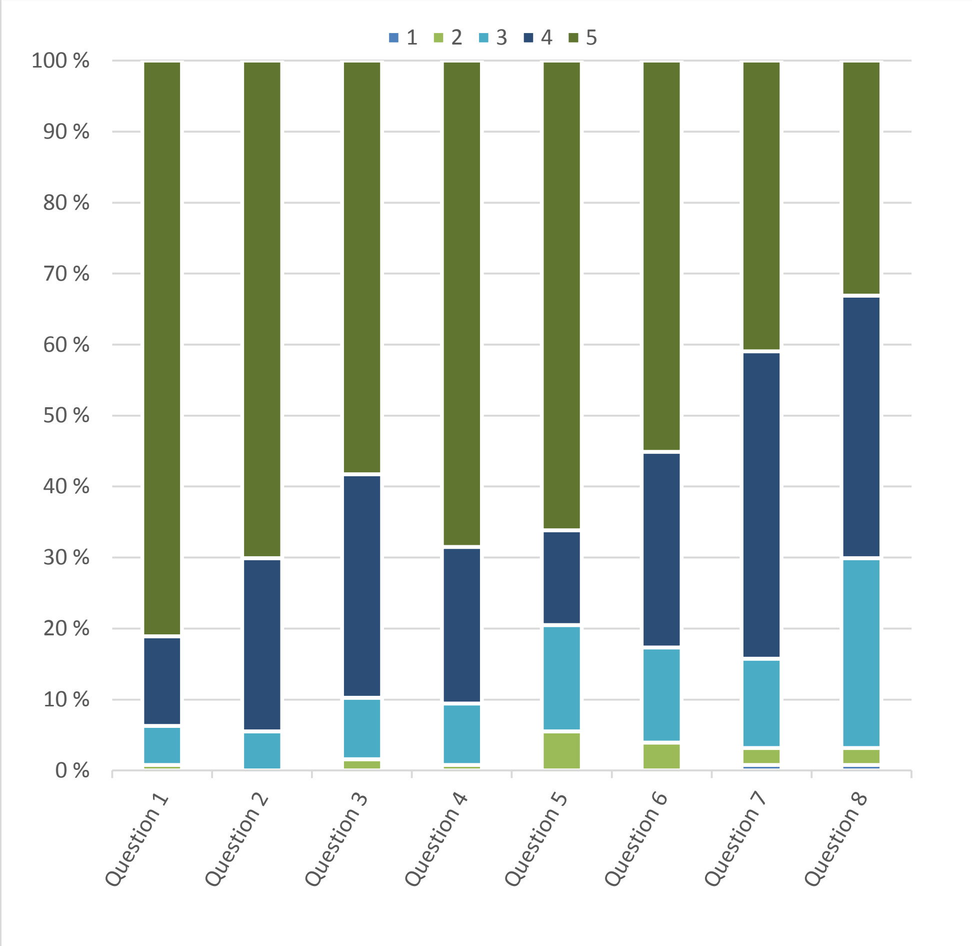

Figure 4.9. *User satisfaction and experiences of micro hydro.*

In questions one through six majority of the respondents fully agree with the statements, while the responses for the last two questions are more dispersed.

4.4.1 Typical household appliances and enterprises in electrified rural Nepal

Household appliances used in rural Nepal are mostly mobile phone chargers and lights. In addition to these low-power appliances, some televisions, radios, and computers can also be found. All these appliances can be served rather easily by photovoltaic systems with the common low-power inverters that are used with single household PV systems. However, some household appliances used in micro hydro powered rural VDCs do not work well in this kind of environment. These include rice cookers, water boilers, iron, and hot plates. These are not too common, but they are good examples of appliances that cannot be used in a small photovoltaic system. Table 4.5 presents common household appliances and their power requirement, and has been prepared based on the household questionnaire and ABS Renewable Energy Information Library (ABS Alaskan, 2008).

Table 4.5. *Power requirements of various household appliances.*

Appliance	Power requirement (W)	Can be used with small PV systems (>130 W_p panel)
Incandescent lamp	40	Yes
Energy saving lamp	15	Yes
Led lamp	7	Yes
Mobile charger	5	Yes
Television (25”, CRT)	150	Limited usage
Television (LCD)	213	Limited usage
Radio	10	Yes
Laptop	100	Yes
Rice cooker	600	No
Water boiler	1,200	No
Iron	1,000	No
Hot plate	1,200	No

Some examples of micro enterprises that can be found in the electrified VDCs are presented in table 4.6. It can be seen that only one of the enterprises can work with a small photovoltaic system. Thus it can be concluded that SHS is a major limiting factor for rural enterprises. However, larger photovoltaic systems such as the micro grid presented in this thesis are capable of providing electricity for all the enterprises listed above.

Table 4.6. *Micro enterprise examples.*

Micro enterprise	Power re-quirement (W)	Utilization rate (%)*	Services/goods provided
Electronic services	250	90	Internet, printing, scanning, electronic repairs, mobile charging
Allo manufacturing	1,500	70	Allo (fabric) production
Rice processing and manufacturing	15,000	80	Rice huller, rice bran oil expeller and rice grinder
Spice manufacturing	1,500	40	Spices
Carpenter	1,000	60	Doors, windows, frames, furniture, buildings
Noodle manufactur-ing	3,500	50	Chowmein noodles

* Utilization rate is an estimate of the time spent using the equipment against the time spent working.

The most favourable enterprises for increasing the load factor of the micro hydro plant have high power requirement throughout the day and can be operated in low-load hours. All the previously mentioned enterprises can be operated throughout the day apart from the electronic services and the carpenter. All the manufacturing enterprises have high power requirement for rural standards, and are therefore good options for increasing the load factor of the micro hydro.

4.5 Rural electricity in Nepal

Nepal is facing energy crisis because the nation's energy consumption exceeds its production rate. The World Bank conducted a study called Power and People: The Benefits of Renewable Energy in Nepal. The study showed that due to the high poverty and the difficult terrain in Nepal, the country is having great difficulties to provide electricity for its population. To overcome these difficulties, a decentralized electricity service is used throughout the rural area while constructing larger power plants to support the national grid. AEPC is the main promoter of the rural electrification and it aims to electrify rural households and support income generating activities in these communities. (Banerjee, et al., 2011)

4.6 Environmental aspects of photovoltaic systems and micro hydro

A comparison of the environmental effects of photovoltaic and micro hydro is given in table 4.7. Both technologies release zero greenhouse gas emissions from electricity generation, which is their main environmental advantage against traditional energy sources. Other minor environmental effects to observe are noise, wildlife, land use, waste and other important characters.

Noise emission from photovoltaics is zero whereas in micro hydro there is some noise from the powerhouse. The volume, however, is low enough not to have any significant effects on the environment around the powerhouse. Photovoltaic systems have no effect on the wildlife around it, but in micro hydro it is important to measure the river flow throughout the year and design the flow rate in the turbine so that the river flow will be sufficiently high throughout the year. In this way the ecosystem of the river stays intact. Land use by photovoltaic systems is significant and therefore needs to be well designed to minimize the effect on cultivated land areas. This can be done by using roof-mounted panels for SHS and ground-mounted panels in wasteland areas that have no use otherwise. Land use by micro hydro is insignificant only taking up a small area for the canal next to the river and the powerhouse. Both technologies do not produce waste from their operation apart from the replaced batteries in photovoltaic systems every eight years. These can be recycled in order to achieve minimal level of waste from operation. Maintenance need and capacity increase are other important characteristics when looking at the environmental effects. Photovoltaic systems are superior to micro hydro in these categories because they require very little maintenance and their capacity can be easily increased.

Table 4.7. *Comparison of the environmental effects of photovoltaic and micro hydro (IPCC, 2011).*

Environmental effects	Photovoltaics	Micro hydro power
Greenhouse gas emission	Zero	Zero
Noise	Zero	Some noise at power house
Wildlife	No effect	Some effect on the ecosystem of the river, if majority of the water is directed to the canal
Land use	Ground mounted panels take up some space, but can be mounted to non-cultivate areas.	Canals used to guide the river flow to the penstock take up very little space
Waste	Batteries need to be replaced in 8 year cycles, which produces some hazardous waste that need recycling	Zero
Other important characteristics	Easy to increase capacity	Very hard to increase capacity
	Low maintenance need	Medium maintenance need, mostly of cleaning the canal

Both technologies offer a renewable source of electricity with zero emissions. The main competitor against them is the use of fossil fuels, but they have significant drawbacks. Typically, the most popular method of providing off-grid electricity in rural areas is the use of diesel generators. However, since the diesel prices have been rapidly escalating while the solar panel prices have experienced rapid declining, the diesel option has become uneconomical (Energy Alternatives India, 2013). Another drawback is the need to transport the fuel to the generator location; if we were to use a 40 kW diesel generator for 24 hours at full load we would need approximately 360 litres of diesel (Diesel Service & Supply, 2013). Obviously, it would not have to operate at full power for the whole period, but this gives an idea of the amount of fuel it would require. Both the PV technologies and micro hydro are excellent alternatives to traditional burning of fossil fuels due to their zero emissions and zero need for fuel.

An interesting finding has recently undermined the environmental performance of large-scale hydro. A study conducted in Singapore suggested that greenhouse gas emissions from hydropower are likely greater than previously assumed. The emissions are believed to emanate from the man-made reservoirs that produce methane gas from the bacteria inside these low oxygen waters. (Li & Lu, 2012) Estimates show that all of the world's large reservoirs could emit up to 104 teragrams of methane annually, which is around the same as the estimates for the emissions of burning fossil fuels (80 – 120 Tg) (National Aeronautics and Space Administration, 1997). However, more information and understanding is needed to obtain more precise estimates of these emissions, but it is important to bear in mind that the emissions are most likely higher than previously predicted. This is most likely not affecting run-off-river type micro hydro, but in case the river has insufficient flow and a small reservoir is needed, it is good to know that the reservoir might have negative effect on greenhouse gas emissions.

5 DISCUSSION OF THE RESULTS

Discussion of the results is divided in six categories. These categories are LCOE and household number, LCOE and power distribution network length, summary of the benefits and limitations of each technology, questionnaire, environmental characteristics of photovoltaic and micro hydro and electricity in Nepal.

This chapter is used to present the main findings of the calculations and literature review and to analyse possible sources of error. The focus is in evaluating the calculations in this thesis to provide trustworthy information of rural electrification by micro hydro and photovoltaic technologies.

5.1 LCOE and household number

The levelized cost of electricity with different production methods changes according to the required electricity generation in kWh and the PDN length. The three different capacity factors presented in the results all produce slightly different outcomes. The LCOE of micro hydro ranges from 24 NPR/kWh (~0.19 EUR/kWh) to 57 NPR/kWh (~0.46 EUR/kWh) depending on the number of households and the load factor. The average small scale hydro LCOE is 0.23 USD/kWh (~0.18 EUR/kWh), which is around 23 NPR/kWh (~0.18 EUR/kWh). This value was calculated with a 50% load factor. (OpenEI, 2014) It is almost the same value as presented with the 40% load factor for micro hydro in RVWRMP. Therefore, the micro hydro LCOE values obtained in this thesis are trustworthy.

The LCOE values of solar PV systems with battery backup presented in this thesis range from 30 to 34 NPR/kWh (~0.24 – 0.27 EUR/kWh) for residential SHS systems and 20 to 35 NPR/kWh (~0.16 – 0.28 EUR/kWh) for commercial PV micro grids. A recent study from Germany indicates that the average LCOE of commercial scale PV systems without battery backup is around 8 NPR/kWh (~0.064 EUR/kWh) and around 11 NPR/kWh (~0.088 EUR/kWh) for residential small-scale PV systems without battery backup (Fraunhofer Institute For Solar Energy Systems ISE, 2013). These values are much lower than the ones presented in this thesis, but they do not include any battery backup, transportation, and PDN costs. In our calculations the battery and charge controller account for approximately half of the annualized costs for SHS, and in micro grid the same value is about 20 percent. When we reduce the transportation and PDN (if necessary) costs, we are left with almost the same LCOE value for both systems. Comparing with the Institutes' discount rate, component lifetime and system sizes, it can be seen that there are even more factors suggesting that our results would be even lower if exactly the same parameters were used. The discount rate used in Fraunhofer Institute's study was 4.7% while in this thesis it was 12%. The system lifetime in the Institute's study was assumed 25 years for the whole system, while in this thesis different values were used for different components. These were 20 for the module and 10 for the BoS. However, the average annual solar radiation used in Fraunhofer Institute's study was 2,000 kWh/m^{2}a while it is around 2,200 kWh/m^{2}a in Far-West Nepal. This value affects the sunshine hours used in our calculations. Summing up all these uncertainties, we can say that the results of this thesis adequately correspond to the findings of the Fraunhofer Institute.

5.1.1 Effect of household number on the LCOE

There were three different scenarios based on different load factors in the LCOE and household number calculations. The first scenario was the current one in use in RVWRMP in which the load factor of the micro hydro was 40%. In this scenario, the micro grid offered a better solution for electricity generation for an averaged size VDC with less than 470 households (presented in figure 4.1). This means that if the planned consumption leads to around 40% load factor and the VDC is smaller than average, the micro grid powered by the centralized PV centre is the better option. However, if the consumption is expected to grow to around 60% load factor, the micro grid is no longer the best alternative for majority of VDC configurations.

In the second and third scenarios, the load factor drops down to account only for the lighting load and a reduced lighting load. These scenarios were included to demonstrate the benefits of solar PV systems, which originate from the modular nature of a PV system. We can easily match the current electricity consumption in every scenario to minimize the extra electricity generation. When the electricity consumption decreases, the PV systems become even better options to micro hydro.

This is a common problem with many electricity production methods in off-grid situations. Electricity usage patterns among consumers are everything but constant. They are changing both daily and seasonally whereas the electricity generation is either steady or only during sunshine. This limitation can be overcome in the solar PV system by employing a battery backup to support the VDC during night. For micro hydro, however, there is no obvious solution. The current plants are run-off-river type of plants without any dams because the river flow throughout the year is enough for the generator to produce the designed power at all times. This means that the best way for micro hydro to compete with solar power is by enhancing the load factor. If it can be raised by about 20% from the current status, the micro hydro will be a better option in majority of the cases.

Building a micro grid should be considered in smaller VDCs with around 200 or less households (figure 4.1) where it offers a few key benefits over micro hydro. Traditionally, the location of the village to be electrified is not right next to the possible micro hydro power plant location, which means that there will be extra PDN length versus the micro grid case. The micro grid PV system can often be built very close to the electricity demand centre because of different mounting equipment available. This also highlights another benefit, the possibility of building the PV system to stable grounds to avoid landslides. Modularity and low maintenance need are also important factors when discussing the benefits of micro grids.

5.2 LCOE and power distribution network length

The average PDN cost in RVWRMP is 270,000 NPR/km (~2,178 EUR/km) including all necessary equipment, and it has 3-phase and 1-phase wires for different parts of the grid. Chaurey and Kandpal introduced a value of 240,000 NPR/km (~1,936 EUR/km) for a 400 V 3-phase PDN, which is somewhat cheaper than the one obtained from RVWRMP data. However, the terrain in which the RVWRMP PDN has been built is very rugged, which can increase the cost by 10% or even more in remote locations (Chaurey & Kandpal, 2010). Thus the costs can be considered comparable, and the value derived from RVWRMP data is trustworthy.

5.2.1 Effect of PDN length on the LCOE

The single household PV system is a great way to produce electricity for households outside the VDC, but the micro grid and micro hydro offer better alternatives for larger clusters. However, the current subsidy policy of the Nepal government supports only very small SHS systems (most systems are around 20 W_p) and therefore it is not beneficial for private households to invest in larger PV systems. The exact same amount of subsidy is provided for a 21 W_p system and a 200 W_p system. The average PDN cost is 270,000 NPR/km and the overnight cost of a 280 W_p SHS system with battery backup is 91,000 NPR (~734 EUR). Thus, if one household is located over 300 meters away from the nearest grid connection, a single household PV system with 280 W_p cell is cheaper to construct. However, connecting a single household to the grid can be done by simple single-phase wire, which means that the actual distance at which the SHS becomes the better option is in fact somewhat longer than 300 meters. This is because building a single-phase grid line is cheaper than the average cost per km of the PDN. The situation also changes depending on the size of the system to either a shorter or a longer distance. It is important to remember that because of the restrictions of the inverters in SHS systems, the high power appliances cannot be used.

The average PDN length is around 19 km and the average line length per household is 40 meters in RVWRMP VDCs. Figure 4.4 shows that the micro grid and the micro hydro are equally good alternatives for the average VDC with 417 households. This is purely a coincidence, but it is a good reminder of just how similar these two electricity sources are. In addition, the SHS system is not a good option for the average size VDC until the PDN length exceeds 50 kilometres. The purple straight in figure 4.4 represents the 80% load factor, which clearly shows just how cheap the electricity would be if the consumption was higher.

Figures 4.4 to 4.6 show that the shorter the PDN the better it is for grid connected systems. In addition, when the load factor decreases the better the SHS system becomes in comparison to grid connected systems. Therefore, it is important to evaluate the VDC and its need for PDN. If the required PDN length is longer than average, shortening of the PDN by replacing some far away households with SHS systems should be considered.

5.3 Summary of the benefits and limitations of each technology

This chapter describes the main benefits and limitations of both PV technologies and micro hydro to highlight the optimal working environment of each technology (table 5.1).

Table 5.1. *Benefits and limitations of SHS, micro hydro and micro grid*.

SHS	Micro hydro	Micro grid
No need for PDN	High cost PDN	High cost PDN
Modularity of capacity	Unable to change capacity	**Modularity of capacity**
Can be applied in every village	Requires a suitable river	Can be applied in every village
Requires very low maintenance	Requires some maintenance	Requires very low maintenance
No high power appliances	**All appliances can be used**	**All appliances can be used**
No micro enterprises	**Micro enterprises**	**Micro enterprises**
Low LCOE with scattered villages	**Lowest LCOE with high load factor**	**Low LCOE with small villages**
Risk of running out of electricity on cloudy seasons (3 days storage)	**Steady electricity throughout the year**	Risk of running out of electricity on cloudy seasons (3 days storage)
	Difficult to achieve high (~60%) load factor	

Note: Fonts in bold represent the main benefits of each technology.

The SHS is unable to power micro enterprises because of its limited inverter capacity. Even for smaller VDCs with low number of households, the micro enterprises are important means to provide for one’s family. Therefore, it is necessary to evaluate the effect of electricity-powered income generating activities to the overall development of the VDC. It is likely that the limitations of the SHS due to the power restrictions will have some impact on the favourability of the micro hydro.

The main benefit of micro hydro is the option of extremely low LCOE. However, a lot of planning and load scheduling is needed for the VDC to use most of the production capacity. If sufficient potential exists for raising the load factor, the micro hydro technology is worth promoting.

The main competitor and the focus of this thesis against micro hydro is the single household PV system because the AEPC does not currently support solar micro grids.

Therefore, the SHS was more closely analysed against micro hydro. SHS is best used in very small clusters or in households far away from the grid. In such situations the modularity and cheap cost of the system will outperform micro hydro options. However, majority of the micro enterprises are unable to operate with SHS systems, an important point to keep in mind.

5.4 Questionnaire

The questionnaire survey was a simple one sided paper form, which was filled out by one representative from each household under the supervision and guidance from RVWRMP staff. The forms were translated to English and analysed. The results showed that the average power requirement of a household was 130 watts in Pouwagadhi and 182 watts in Chhatara. However, when analysing the project data, it can be seen that the same values are 86 watts for Pouwagadhi and 74 watts for Chhatara. While the values provided by the project are simple calculations based on the power requirement and household number in the VDC, the questionnaires were only filled by people interested in the topic. This means that there are probably households in which there is no electricity or only a few lamps among those who were not interested in filling out the form. Figure 4.8 also shows that the power requirement of each household varies greatly and especially in Chhatara we can see that eight households have much higher power requirement (800-1,200 watts) than the average. If the high-power appliances such as water boilers become even more popular, there may be need to start planning how to control their usage.

If we use the current average power requirement (130 and 182 watts) to calculate the maximum power requirement, we can see that it is 32 kW for Pouwagadhi (21 kW) and 123 kW for Chhatara (50 kW). These high values do not include the power requirements of commercial uses of electricity such as a variety of income generating activities. However, the values provided by the respondents are only estimates of their combined load. This means that there is some margin for error, but since majority of the households use only lights and chargers, the values provided by the respondents seem to be in correct range. The sampling of the questionnaire was not random because every household had an opportunity to fill it if they so wished. Thus the actual average power requirement of the VDCs can be expected to be smaller had the sampling been random, i.e. including also the households without electricity. There is a big difference between the power output of the micro hydro plant and the power required by the VDC if all appliances are turned on simultaneously. Fortunately, only a small amount of the power requirement is used for longer periods, e.g. lighting, televisions, and radio. These appliances do not require as much power as a water boiler or a rice cooker, both of which are in the kW range. However, electricity has only been available for three to four years in these VDCs and we can already see that the average power required by a household is growing higher than planned. It would be interesting to study the electricity usage patterns of these VDCs further by measuring the consumption from the hydro plant, rather than relying on assumptions.

One important aspect to monitor is the use of electricity for income generating activities that are main components in the renewable energy approach of RVWRMP. Table 4.3 shows that the percentage of households using electricity for income generating activities are 44 and 13 for Pouwagadhi and Chhatara, respectively. The higher percentage in Pouwagadhi could be, although not entirely, because of the longer period with electricity. A more probable cause could be that the sample is not representing the actual VDC very well. The two VDCs are different in many ways. Pouwagadhi is a small VDC with only 245 households while the Chhatara has 677 households. Pouwagadhi is also situated only an hour away from the nearest road head whereas Chhatara takes about four hours to reach by foot from the nearest road head. This means that in Pouwagadhi it is easier to get products to the market while in Chhatara one has to do almost a day's work for the same result. However, it is important to remember that not all income generating activities produce goods that can be sold at the nearest road head. Increasing the electricity consumption by income generating activities will also increase the load of the power plant during daytime and the amount of money the villagers can spend on local products and services.

The operation and management in the two VDCs was observed very different during the field visit. The plant operator in Chhatara appeared to take more pride in his work and got paid about double the salary of the operator in Pouwagadhi. The plant in Chhatara was operational for most of the day whereas in Pouwagadhi it was usually operating at night only. This is understandable as the powerhouse in Pouwagadhi had only one room, which means that the operator has to listen to the loud machinery all the time. In Chhatara there were different rooms for the machinery and the operator, which makes the loud noise slightly more bearable.

Approximately half of the households in the VDCs had considered buying more electric appliances. This progress is in the right direction as it increases the load factor of the plant, further decreasing the LCOE. People are also extremely proud of their appliances and willing to present them to visitors (figure 5.1).

Figure 5.1. *Household in Chhatara.*

The satisfaction of the consumers was also clearly stated in the part of the questionnaire presented in table 4.2. Over 80% of the respondents were fully satisfied with the availability of electricity. It is easy to understand their satisfaction considering the previous situation without any electric supply. There have been some power cuts, but the operator and volunteers from the villages have fixed them as soon as possible. Landslides affect most of Nepal during the rainy season. An example of this and the destruction it may cause to a hydro power plant is illustrated in figure 5.2. Landslides are a major problem in areas where deforestation has increased their probability.

Figure 5.2. *Landslide.*

The cost of electricity is very low and 70% of the households are completely satisfied with it. However, many consumers informed that they would be happy to pay more for it. It would be a good idea to review the cost of electricity annually in all VDCs to ensure there is enough money for the operation and maintenance and to keep it in line with inflation. Around eighty percent of the households agree that electricity has had a positive effect on the general quality of life. It is assumed that for most users this comes from the bright lighting available at night compared to the kerosene lighting that was used before. Kerosene is also more expensive compared to electric lights. Therefore, the households can save money by switching to electric lighting, which is important because the money saved can be spent on local products and services. Lighting is also important for children so that they can do their homework and study in the evenings. This is probably why around 70 percent of the households feel that electricity has had a positive effect on the household's school performance. The television, radio and cell phones that can now be used are affecting the information and communication level in the households. In addition, lighting is also important in social gatherings that are easier to organize than before. Majority of the households also feel that electricity has had a positive effect on their information and communication level.

The last two questions of the questionnaire have more dispersion among respondents. It is harder to evaluate if electricity has had a positive effect on the household's general health or the empowerment of women as the impacts are not so clearly visible. Nevertheless, most respondents are agreeing to the statement 75 to 100 percent. This is very important in RVWRMP because traditionally the female population in Nepal faces discrimination and segregation. Therefore, if we can make a difference on the mind-set of the female population so that they start to recognize themselves as equal members in the society through availability of electricity, it is important that we do so. Electricity allows women to study and be active members in the community by reducing their daily workload of household chores. It is very common in the rural areas of Nepal that the husband goes to work in India while the wife stays at home taking care of the children and the household. This kind of lifestyle is very exhausting for the female, but with the help of a few electric appliances the workload becomes considerably smaller. The improved situation is shown in figure 5.3 where a mother is showing her electric appliances.

Figure 5.3. *Empowering the female population.*

The general health of the household has increased according to the respondents. This is most likely because of the lighting and increased level of information.

5.5 Environmental characteristics of photovoltaic and micro hydro

Micro hydro and photovoltaic systems are both exceptionally good sources of electricity. The greatest advantages of both systems is the zero emissions and zero need for fuel. However, both systems also have drawbacks. The biggest one in photovoltaic systems is the need for replacing the batteries every eight years in off-grid installations and the restrictions of inverters in SHS. The biggest drawback of micro hydro is the difficulty of achieving high load factors and the impossibility of increasing the capacity.

If the photovoltaic and micro hydro technologies are compared from an environmental point of view, they can be considered similar in many ways. Both offer significant advantages over the burning of fossil fuels, which is the current scenario in many least developed countries. Therefore, Nepal is in a good position energy wise, as it has economically feasible renewable energy sources available throughout the country. The electrification of rural VDCs can be achieved economically and environmentally with the energy sources presented in this thesis.

5.6 Electricity in Nepal

The current scheme of constructing electricity services from the demand point of view is suitable for a least develop country like Nepal because it supports firstly the end user and secondly the supply. This way the capacity increases in line with the electricity demand while end users are also supported. When the electricity coverage increases in the rural areas, the power demand begins to raise slowly. Large-scale power plants usually offer alternatives that are more economical over micro-scale settings, but the difficulties come from the demand side. A large-scale plant is very expensive if the capacity cannot be fully utilized, whereas with micro scale plants the utilization of the production capacity is easier. Therefore, it is essential to keep the demand and supply in balance at all times, and for rural settings, a localised grid and a small-scale energy source is a superior alternative.

When the number of localised grids increase among the rural areas, it is possible to start connecting these grids together to increase the coverage of the national grid and the stability of the micro grid. By doing so, the national grid will have more flexibility to change its capacity with seasonal and daily variations. Hydropower is a great electricity source for controlling the supply and demand balance because it can be turned on almost instantly. Thus, grid connected photovoltaic systems work well in cooperation with hydropower since they experience many changes in their electricity generation that can be balanced with hydropower.

6 CONCLUSIONS

Nepal, with its limited national grid and extremely mountainous terrain, is facing big challenges when it comes to providing electricity to its population. The focus of this thesis was the economic comparison of hydropower and solar PV systems for electrifying rural villages of Nepal.

From the results of the LCOE calculations, we can see that the three technologies in question all have their advantages and disadvantages. The single household PV system is the most expensive technology in most cases, but it still shows its strength when the grid connection is far away. The SHS was the focus of this thesis because the AEPC does not currently support solar micro grids, but for future purposes, the micro grid was also studied in this thesis.

Both technologies offer electricity provided by minimal adverse environmental effects. For a least developed country, the renewable energy resources of Nepal are unique. The utilization of these resources will have a significant effect on the rural population of Nepal.

6.1 Economic performance of SHS

The PDN variable, which is the length of the distribution network, shows clearly that the SHS is the best option in scattered villages where a considerable part of the expenses go to construction of the distribution network. The actual level of scatterdness where this happens is harder to point out because there is another variable affecting it. This variable is the number of households in the village. When we combine these two variables to form the lines that represent at which household and PDN length combination the SHS will be the better option, we can easily analyse each combination (figure 4.7). It can be concluded that if the answer to equation 10 or 11 (p. 49) is greater than zero, micro hydro is the better option. However, if it is less than zero, SHS is the better option. By this simple calculation, RVWRMP can easily decide whether to support certain VDCs with micro hydro.

As we change the load factor of the hydro plant, we can see how it affects the competitiveness of the SHS and micro grid. This is due to the fact that the solar systems are calculated to provide exactly the necessary amount of energy needed while the hydro plant is not utilizing all of its production capacity. Therefore, we must try to increase the load factor of the hydro plants and avoid building too big power plants. The best way to increase the load factor of a hydro plant is by increasing the amount of electricity used by income generating activities. This both helps the community to gain important revenue, but also increases the daytime load of the hydro plant. In addition, because the households gain more revenue, they are likely to invest this money on electric appliances to further increase the load factor. However, there are some limitations to the load factor in isolated grids because the power consumption is highly dependent on the time of the day. This can be partly overcome by urging locals to power on their machines used for income generating activities on low demand hours. In addition to working on the low load hours, establishment of more electricity consuming micro enterprises should be encouraged. This way the community will help to improve the cost effectiveness of the micro hydro while they obtain more income.

The SHS is not capable of providing electricity to most common micro enterprises because they require too much power. It is a limitation that needs to be kept in mind when comparing SHS against micro hydro.

6.2 Further actions

The results show that the single household photovoltaic system offers a competitive alternative to micro hydro. The main benefits of SHS are the simplicity and modularity, but with the current subsidy policies for SHS, only the smallest systems are promoted. This is not in favour for the SHS because it promotes a wrong kind of image of the SHS. It is much more than just capable of lighting purposes if the panel size is similar to that of this thesis. Therefore, it would be beneficial if the government would begin supporting larger SHS systems.

Obtaining more detailed information of the consumption patterns of the micro hydro villages would help plan the future monetary support more carefully. If we know at what time and how much electricity is being used in the village, we can obtain more precise calculations for the LCOE values of the competing technologies. In addition, we can analyse how the consumption figures change annually, which will help the community to get the most of their micro hydro plants. This can be done by levelling out the consumption throughout the day. The information would also help to make projections for the future so that the VDC knows how the electricity usage patterns will change. A simple way to obtain this information would be a digital electricity meter that stores the information in digital form to be accessed via computer.

The questionnaire revealed how electricity is affecting the population, but the sample of two micro hydro VDCs is too small to draw comprehensive conclusions for all VDCs with MHP. Therefore, it would be good to conduct a similar survey in all of the micro hydro VDCs of RVWRMP. This way RVWRMP can identify which VDCs are in need for further support in their micro hydro plants and their operation and management.

Another factor that influences the favourability of micro hydro over SHS is the effect of micro enterprises on the development on the VDC. If we find out that the micro enterprises have major impact, we need to reconsider the application limits for the use of SHS. This is because SHS is insufficient to operate the micro enterprises due to the limited inverter capacity.

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APPENDIX 1: SCHEME INFORMATION

Sarake1	Hopari-gad MHS	Upper Rilu MHP	Jadari-gad MHP	Kashegad MHP	Kailash Khola V MHS	Kailash Khola IV MHS	Maubheri Khola MHS	Kukur-falna MHP	Sanni Gad MHS	Riting Gad MHS*	Sailigad MHP	Lower Rilu MHP	Dogadegad MHP
District	Darchula	Bajhang	Bajhang	Bajura	Achham	Achham	Bajhang	Humla	Bajhang	Darchula	Doti	Bajhang	Bajhang
VDC	Sipti	Rilu	Pouwagadhi	Chhatara	Bhataka-tiya	Bhataka-tiya	Koiralakot	Kalika	Kaphal-seri	Sunsera	Gi-richauka	Rilu	Masta
Power Out-put (kW)	**50**	**30**	**21**	**50**	**25**	**35**	**30**	**100**	**100**	**51**	**23**	**22**	**46**
Beneficiary HHs	583	248	245	677	349	430	386	630	992	553	240	250	490
Beneficiary Population	3881	1552	1637	4478	1967	2727	2187	3267	6663	3283	1253	1509	2748
Average subscribed power (W) per HH	86	121	86	74	72	81	78	159	101	92	96	88	94
Walking distance (h) from near-est road-head	6	10	1	6	3		2	40	40km		6km		4
Effective head (m)	185	87		47	22	20	61	66	65		10,5	54	96,5

Transmission and distribution line lenght (m)	34965				7594		14025	19245	33128		9275		30770
Total weight of transported goods (kg)	91442			141662		134970	48989	96959	317076			120163	
Lenght of headrace (m)	2743	930		620	989	672	1115	1292	1680		613	1188	1068
Turbine type	Double Jet Pelton	Double Jet Pelton		Crossflow	Crossflow	Crossflow	Double Jet Pelton	Cross-flow	Crossflow		Crossflow	Crossflow	Double Jet Pelton
Total project cost (NPR)	16 099 555	12 086 570	9 212 136	18 443 161	11 347 054	13 903 046	14 002 373	57 919 107	53 182 585	23 370 788	12 151 049	11 039 169	23 516 597
Cost per kW (NPR)	321 991	402 886	438 673	368 863	453 882	397 230	466 746	579 191	531 826	458 251	528 306	501 780	511 230
Cost of civil components (NPR)	404 866			4 097 736	2 845 522	3 790 903	1 576 365	3 190 401	11 164 215			5 549 020	
Cost of electrical components (NPR)	7 754 962			8 570 100	2 847 470	4 988 895	5 800 632	2 260 000	17 773 445		3 715 725	1 647 200	7 467 160
Cost of mechanical components (NPR)	1 281 715			1 711 837	852 100	1 627 030	986 860	3 717 500	1 482 856		1 487 100	1 054 660	2 384 480
Cost of tools and spare parts (NPR)	71 000			0	19 500	70 000	22 000	216 400	109 000		62 900	32 725	139 400

Cost of transportation and packing (NPR)	502 931			2 056 763	264 498	1 854 461	1 184 608	10 760 109	4 932 809			1 613 603	300 000
Cost of installation, testing and commissioning (NPR)	350 000			600 000	130 500	205 000	355 000	1 240 000	715 000		305 000	275 000	350 000
Cost of contingency (NPR)	536 483			70 072	347 954	103 963	550 608		1 976 772				100 000
Net annual profit (NPR)	81 735				272 051	1 036 238	573 705		413 309				
Investment cost (NPR)	10 901 921			16 738 841	4 157 842	8 423 478	10 476 075	46 106 607	38 154 098				
Operation and maintenance cost (NPR)	362 092				200 821	535 454	346 883		1 245 367				
NPV, 10% discount rate (NPR)	599 599				761 518	1 263 906	956 150	30 205 853	3 915 216				
Payback period (a)	7				7	7	6,7	7	7,6				
B/C ratio	1,09				1,59	1,69	1,09		1,11				
IRR (%)	11,56				12,88	10,19	12,4	14,44	12,6				
Lighting load (kWh/mo)	10500	6300	4410	10500	5250	7350	6300	6300				3300	
End use (kWh/mo)	4374	480	1815	12420	735	735	2386	0				0	

Total consumption (kWh/mo)	14874	6780	6225	22920	5985	8085	8686	6300				3300	
Total generation capacity (kWh/mo)	36000	21600	15120	36000	18000	25200	21600	72000				15840	
Plant factor (%)	41 %	31 %	41 %	64 %	33 %	32 %	40 %	9 %				21 %	

APPENDIX 2: MICRO HYDRO

Component	Total power	Total cost	Cost per kW	Depreciation (NPR)	Recuring annual costs (NPR)	Total annualised costs	Annual electricity generation kWh	LUCE (Levelised unit cost of electricity)	Number of households
Unit	kW	NPR	NPR	NPR	NPR	NPR	kWh	NPR/kWh	
Average(W/O PDN)	44,84615	9038288	201539,9	1327040	471220,2	1798260	126094,3	14,26123	416,8571
Average	44,84615	13584842	407181,6	1994584	471220,2	2465804	126094,3	19,55524	
MHP_Hoparigad	50	16099555	321991,1	2363805	470092	2833897	178488	15,87724	583
Upper Rilu MHP	30	12086570	402885,7	1774601	462758	2237359	81360	27,4995	248
Jadarigad MHP	21	9212136	438673,1	1352565	445561,7	1798127	74700	24,07131	245
Kashegad MHP	50	18443161	368863,2	2707903	500972	3208875	275040	11,66694	677
Kailash Khola V MHS	25	11347054	453882,2	1666023	392821	2058844	71820	28,66672	349
Kailash Khola IV MHS	35	13903046	397229,9	2041304	535454	2576758	97020	26,55904	430
Maubheri Khola MHS	30	14002373	466745,8	2055888	490883	2546771	104232	24,43367	386

HH	**LCOE_1**	**LCOE_2**	**LCOE_3**	**LCOE_4**	**LCOE_5**	**PDN**	**LCOE_12**	**LCOE_22**	**LCOE_32**	**LCOE_42**
586,5599	15,01109	8,577436	23,85336	34,07705	11,79426	2,5478865	14,744434	7,7056777	21,428976	30,61329
558,6284	16,27366	8,916813	24,79715	35,42535	12,59524	2,8309849	14,832809	7,7518652	21,557418	30,79676
532,0271	17,4761	9,24003	25,69599	36,70945	13,35807	3,1455388	14,931003	7,8031847	21,700131	31,00062
506,6925	18,62129	9,547855	26,55204	37,9324	14,08457	3,4950431	15,040108	7,8602063	21,858701	31,22714
482,5643	19,71194	9,841021	27,36732	39,09711	14,77648	3,8833813	15,161335	7,9235637	22,03489	31,47882

459,585	20,75066	10,12023	28,14377	40,20636	15,43544	4,3148681	15,296032	7,9939607	22,230656	31,75847
437,7	21,73991	10,38614	28,88326	41,26279	16,06303	4,7942979	15,445696	8,0721797	22,448173	32,06918
416,8571	22,68206	10,63939	29,58753	42,26892	16,66072	5,3269976	15,611989	8,1590897	22,689859	32,41443
396,0143	23,62421	10,89264	30,2918	43,27504	17,25842	5,9188863	15,796759	8,2556563	22,958399	32,79803
376,2136	24,51925	11,13322	30,96085	44,23086	17,82623	6,5765403	16,002059	8,3629525	23,256776	33,22426
357,4029	25,36953	11,36178	31,59646	45,13888	18,36566	7,307267	16,23017	8,4821706	23,588307	33,69784
339,5327	26,17731	11,57891	32,20028	46,00151	18,87811	8,1191855	16,483626	8,6146351	23,956674	34,22404
322,5561	26,94469	11,78518	32,77391	46,821	19,36494	9,0213173	16,765245	8,7618179	24,365972	34,80872
306,4283	27,67371	11,98114	33,31886	47,59952	19,82742	10,023686	17,078154	8,9253543	24,820746	35,45835
291,1069	28,36627	12,1673	33,83656	48,33912	20,26679	11,137429	17,425831	9,1070615	25,326051	36,18017
276,5515	29,02421	12,34415	34,32838	49,04173	20,68418	12,374921	17,812139	9,3089583	25,887502	36,98219
262,724	29,64925	12,51216	34,79561	49,70921	21,08071	13,749912	18,24137	9,5332881	26,511335	37,87332
249,5878	30,24304	12,67177	35,23947	50,34332	21,4574	15,27768	18,718293	9,7825435	27,204483	38,86346
237,1084	30,80714	12,8234	35,66115	50,94572	21,81527	16,9752	19,248208	10,059494	27,974648	39,96363
225,253	31,34303	12,96745	36,06173	51,51801	22,15524	18,861333	19,837002	10,367217	28,830387	41,18603
213,9903	31,85213	13,10429	36,44229	52,06168	22,47821	20,747467	20,425797	10,674939	29,686126	42,40843
203,2908	32,33577	13,2343	36,80383	52,57816	22,78503	22,822213	21,07347	11,013434	30,627438	43,75308
193,1263	32,79523	13,3578	37,14728	53,06882	23,07652	25,104435	21,785911	11,385779	31,662882	45,23218
183,4699	33,23172	13,47513	37,47356	53,53495	23,35343	27,614878	22,569597	11,795357	32,80187	46,8592
174,2964	33,64639	13,58659	37,78353	53,97777	23,61649	30,376366	23,43165	12,245894	34,054757	48,64892
165,5816	34,04032	13,69248	38,078	54,39845	23,8664	33,414003	24,379909	12,741485	35,432933	50,61762
157,3025	34,41455	13,79307	38,35774	54,7981	24,10381	36,755403	25,422994	13,286634	36,948926	52,78318
149,4374	34,77007	13,88864	38,6235	55,17777	24,32936	40,430943	26,570387	13,886298	38,616519	55,16529
141,9655	35,10782	13,97942	38,87597	55,53845	24,54362	44,474037	27,83252	14,545929	40,450871	57,78562
134,8673	35,42868	14,06567	39,11582	55,88109	24,74717	48,921441	29,220866	15,271523	42,468658	60,66799
128,1239	35,7335	14,1476	39,34368	56,20661	24,94055					
121,7177	36,02307	14,22544	39,56014	56,51585	25,12426					

115,6318	36,29817	14,29939	39,76578	56,80962	25,29878					
109,8502	36,55951	14,36964	39,96113	57,08871	25,46457					
104,3577	36,80778	14,43637	40,14672	57,35385	25,62208					
99,13984	37,04365	14,49977	40,32303	57,60572	25,77171					
94,18284	37,26771	14,56	40,49053	57,84501	25,91386					

APPENDIX 3: SHS AND MICRO GRID

Variables	Unit	SHS_total	SHS_ligh-ting load	SHS_ligh-ting load_0,7	Mic-rogrid1_1
Number of households		416,86	416,86	416,86	416,86
Diversity factor		1,00	1,00	1,00	1,10
Inverter efficiency		0,90	0,90	0,90	0,95
Total DC energy required per day	W	933,60	642,37	449,66	335178,86
Operating voltage	V	12,00	12,00	12,00	120,00
Charge to be supplied every day	Ah	77,80	53,53	37,47	2793,16
Battery efficiency		0,85	0,85	0,85	0,90
Charge to be given by battery per day	Ah	91,53	62,98	44,08	3103,51
Maximum depth of discharge (MDOD)		0,70	0,70	0,70	0,70
Days of autonomy	d	3,00	3,00	3,00	3,00
Size of the battery	Ah	392,27	269,90	188,93	13300,75
Nearest available battery size	Ah	400,00	270,00	190,00	13300,00
Efficiency of charge control-ler		0,85	0,85	0,85	0,90
Charge to be supplied to bat-tery per day	Ah	107,68	74,09	51,86	3448,34
DC energy to be provided by the PV array	Wh	1292,19	889,10	622,37	413801,06
Loss of energy due to ambi-ent temperature		0,10	0,10	0,10	0,10
Loss of energy due to dust etc.		0,10	0,10	0,10	0,10
Loss of energy due to mis-match among solar cells		0,15	0,15	0,15	0,10
DC energy to be generated for providing the required value	Wh	1798,08	1237,18	866,03	575804,17
Equivalent hours of full sun-shine (EHFS)	h	6,80	6,80	6,80	6,80
PV requirement	W_p	264,42	181,94	127,36	84677,08
PV requirement per hou-sehold	W_p	264,42	181,94	127,36	203,13
PV module capacity for SHS	W_p	270	185	130	

Total PV capacity	W_p	112551,43	77118,57	54191,43	84700
		Avg. Total load	avg. Lighting load	70% lighting load	Combined average load

Component	Capital cost (NPR)	Life (years)	CRF (fraction)	Annualised costs (NPR)
SHS_1				
Module_280 W_p	22937,6	20	0,13	3070,86
Battery_400Ah	50614,44	8,5	0,19	9822,23
Charge controller	4150	5	0,28	1151,25
Balance of systems	12800	10	0,18	2265,40
Transportation costs	16290,36762	20	0,13	2180,93
Annual O&M costs				720,00
Total annualised costs	90502,04233			19210,67
Annual electricity generation kWh				625,46
LCOE (Levelised cost of electricity)				30,71
SHS_2				
Module_185 W_p	14745,6	20	0,13387878	,122939
Battery_280Ah	35430,10963	8,5	0,194059759	6875,558541
Charge controller	4150	5	0,277409732	1151,250388
Balance of systems	8457,142857	10	0,176984164	1496,78036
Transportation costs	11300,91345	20	0,13	1512,95
Annual O&M costs				560
Total annualised costs	62782,85249			13570,66473
Annual electricity generation kWh				413,253
LCOE (NPR/kWh)				32,83863573
SHS_3				
Module_130 W_p	10649,6	20	0,13387878	1425,755456
Battery_200Ah	25307,22116	8,5	0,194059759	4911,113244
Charge controller	3470	5	0,277409732	962,6117698
Balance of systems	5942,857143	10	0,176984164	1051,791604
Transportation costs	8166,542095	20	0,13	1093,33
Annual O&M costs				400
Total annualised costs	45369,67831			9844,598767
Annual electricity generation kWh				290,394
LCOE (NPR/kWh)				33,90083392

Item	**Symbol**	**microgrid1_1**	**microgrid1_2**	**microgrid1_3**
N.O. households		416,8571429	625,2857143	208,4285714

Lenght of PDN	km	19,41912326	29,12868489	9,709561629
PV cost	NPR/W	51,2	51,2	51,2
PCU cost	NPR/W	60,48	60,48	60,48
Total cost per kW_p	NPR/kW_p	131549,3059	131549,3059	131549,3059
Battery capacity	Ah	13300,00	19960,00	6660,00
Battery cost	NPR/Ah	126,5361058	126,5361058	126,5361058
PV capacity	kWp	84,70	127,02	42,34
Cost of microgrid (W/O PDN)	NPR	11142226,21	16709392,83	5569797,611
Cost of PV	NPR	4336640	6503424	2167808
Cost of Battery	NPR	1682930,207	2525660,672	842730,4648
Cost of PCU	NPR	5122656	7682169,6	2560723,2
Cost of transporta-tion	NPR	1387914,093	2081704,337	693968,9315
Cost of PDN, SC	NPR	6206699,957	9310049,936	3103349,979
Total cost of mic-rogrid	NPR	18736840,26	26019442,77	8673147,589
NPR/kW_p of mic-rogrid	NPR/kW_p	221214,1707	204845,243	204845,243
C_opv*CRF	NPR	580584,0727	870808,4736	290269,4912
C_otra*CRF	NPR	185841,6971	278740,2107	92922,43992
C_obatt*CRF	NPR	326589,0307	447041,939	149163,2923
C_opcu*CRF	NPR	994101,3896	1359744,019	453248,0064
C_opdn*CRF	NPR	1204470,699	1647878,839	549292,9462
Annualised capital cost	NPR	3291586,889	4604213,481	1534896,176
Annual O&M cost	NPR	192000	192000	192000
Total annual cost	NPR	3483586,889	4796213,481	1726896,176
Annual energy ge-neration	kWh	189202,86	283737,276	94579,092
Levelised unit cost of electricity	NPR/kWh	18,41191454	16,903713	18,2587519
		Combined average load		

Assumptions used in solar PV:

Battery cost	126,5361058	nPR/Ah
PV cost	51,2	NPR/W
Cost of PV	4336640	0,389207679
Cost of battery	1682930,207	0,15104075
Cost of PCU	5122656	0,459751571
Total cost	11142226,21	
Total cost/kW_p	131549,3059	NPR/kW_p
Cost of PCU / W	60,48	NPR/W

balance of systems	45,71428571	NPR/W
charge controller	ebay	
charge controller	22,43243243	
charge controller	26,69230769	

Battery price:

Number	capacity	price	INR/Ah	NPR/Ah	Brand
1	100	9000	90	144	Okaya
2	135	9478	70,20741	112,33185	Okaya
3	150	10007	66,71333	106,74133	Okaya
4	150	11093	73,95333	118,32533	Okaya
5	150	11858	79,05333	126,48533	Okaya
6	150	12943	86,28667	138,05867	Okaya
7	150	13838	92,25333	147,60533	Okaya
8	200	15494	77,47	123,952	Okaya
9	100	8400	84	134,4	Exide
10	100	9100	91	145,6	Exide
11	135	10200	75,55556	120,88889	Exide
12	150	10200	68	108,8	Exide
13	150	11800	78,66667	125,86667	Exide
14	150	13100	87,33333	139,73333	Exide
15	150	13400	89,33333	142,93333	Exide
16	150	11300	75,33333	120,53333	Exide
17	180	14400	80	128	Exide
18	150	13900	92,66667	148,26667	Exide
19	200	16200	81	129,6	Exide
20	135	9200	68,14815	109,03704	Amaron
21	135	9850	72,96296	116,74074	Amaron
22	150	10650	71	113,6	Amaron
23	150	11800	78,66667	125,86667	Amaron
24	150	12900	86	137,6	Amaron
25	135	9150	67,77778	108,44444	Lu-minous
26	150	9850	65,66667	105,06667	Lu-minous
27	150	11200	74,66667	119,46667	Lu-minous
28	150	13600	90,66667	145,06667	Lu-minous
Average	**146,60714**	**11568,25**	**79,08507**	**126,53611**	
information from batterybhai.com					
http://www.batterybhai.com					

APPENDIX 4: DISTRIBUTION NETWORK COST

Kailash khola V	Description	Total cost	T&D cost	Hoparigad	Sarake2	Sarake5	T&D cost	Mau bheri khola	Electrical:	Sarake3	T&D cost
1	Generator: KEL Synchronous, 3 Ph. 50 KVA, Brush-less	250		C.	Electrical:			S N	Description	Total	
2	ELC 25 kW	140		1	110 KVA, synchronous generator, 3 phase, 50 HZ and brushless	400000		1	63 KVA, synchronous generator, 3 phase, 50 HZ and brushless,KEL	272000	
3	Heater for ballast load 30 kW	25		2	50 kW ELC, 3-Phase	250000		2	30 kW ELC Set with ballast tank	290000	
4	Transmission cable :			3	Ballast Tank, capacity 60 kW	25000		3	Main switch, 70 A, three-Phase, 70 A MCCB, 90 A TP MCCB at	20000	

									generator side		
	Weassel	179280	179280	4	Main switch, 125 A, three-Phase	10000		4	70 mm2 4 core cupper armored ca-ble	57000	
	Squirrel	421800	421800	5	Distribution Boxes at PH, N, T and 78	48000	4800 0	5	95 mm2 4 core alumi-num un-armored ca-ble	25000	
5	Main switch HRC fuse type, 3 phase 60 amp, Havells	12000		6	125 A MCCB, Three phase	10000		6	Powerhouse wiring	8000	
6	MCCB	-		7	Earthing Sets with 8 SWG copper wire	280000	2800 00	7	Energy me-ter(subme-ter)	19300 0	280000
	MCCB 75 Amp, 10 kA breaking capac-ity (L & T) (Genera-tor side)	8000		8	Lightning arres-tor , 0.5 kV	36000	3600 0	8	Squirrel Con-ductor	73712 1	36000
	MCCB 60 Amp, 10 kA breaking capac-ity (L & T) (includ-ing for 2 trans-formers)	22500		9	Salt	5000		9	Weasel Con-ductor	10424 7	104247
7	MCB (for 289 houses load con-trol) with cover	86700		10	Transformer and accessories	953000	9530 00	10	Rabbit Con-ductor	55598 4	555984
8	Transformer 35 kVA	500000	500000	11	Powerhouse wi-ring	6000		11	Shackle insu-lator"Small	19285 0	192850

									Size", 200 gm		
9	Insulator			12	150 mm2 4-core, armored cu cable for connection	70000		12	Shackle insulator " Medium Size" 600 gm	58200	58200
	Medium sackle insulator with 'D' iron , nut , bolt etc.for LT line	69300	69300	13	185 mm 2 , armored 4-core Aluminium cable upto first pole	20000		13	Stay Sets	185925	185925
	Disk insulator for HT line	40800	40800	14	Rabbit	109296	109296	14	0.5 kV lightening arrestors	64500	64500
	Pin insulator for HT line	75600	75600	15	Squirrel	2064260	2064260	15	6 mm2 , concentiric al. Service wire	254760	254760
10	Cross arm and brasing set :		0	16	4 mm 2 service wire	262350	262350	16	Earthing sets, 600x600x3 mm with 8 SWG wire sets in distribution	262500	262500
	1.5 m long with brasing set	48400	48400	17	Small With D iron + Pole bolts	178320	178320	17	Steel Tubular Poles: 6 m	986000	986000
	2 m long with brasing set	21000	21000	18	Medium with D+Pole bolts	7200	7200	18	Steel Tubular Poels: 7 m	1568000	1568000
11	Lightning Arrestors		0	19	Pin insulators	213900	213900	19	Bitumen paint	0	0

	9 kV	40000	40000	20	Disc insulators	27000	27000				
	0.5 kV	16200	16200	21	Stay set	200000	200000				
12	D. O. fuse	18000	18000	22	Wooden Poles: 6 m	229500	229500				
13	D. O. operating rod	8500	8500	23	Wooden Poles: 7 m	100100	100100				
14	Earthing Arrangement		0	25	Steel tubular poles: 9 m	2160000	2160000				
	Cupper: plate 600*600*3 mm including 8 SWG wire	90000	90000	26	H-Pole Sets for transformers	88000	88000				
15	Stay set (1.5 m rod)	44400	44400	27	Bitumen Paint	2000					
16	6mm2 Service wire (Concentric cable 30m x 289 house)	190740	190740								
17	Power Cable:										
	Power Cable: 35 mm2 armoured copper (4 cores) (Inside PH)	50000									
	50 mm2 armoured aluminium cable (4 cores) (for Main switch to First pole and 100 KVA Transformer)	112500									
18	Power house wiring	7000									

19	Pole :	-									
	Metal pole (9 m long steel)	336000	336000								
	Wooden	33750	33750								
	Total	2,847,470	2133770		Sub - Total (C)	7754926	6956926		Sub - Total (C)	5835087	4548966
	T&D line (NPR/km)		280981		T&D line (NPR/km)		198968,3		T&D line (NPR/km)		324347
	Household number	349			Household number	583			Household number	386	
	T&D cost / HH	6113,954			T&D cost / HH	11932,98			T&D cost / HH	11784,89	
	T&D lenght / HH	0,021759			T&D lenght / HH	0,059974			T&D lenght / HH	0,036334	
	Average T&D line cost	268098,8	NPR/km								
	Average T&D line lenght	18,86133	km								
	Average T&D line cost	4546554	NPR								
	Average HH	439,3333									
	Average T&D line cost / HH	10348,76	NPR/HH								
	Average T&D lenght / HH	0,039356	km/HH								